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Review Article

Climate Change and Emerging Infectious Diseases: A Global Review of Shifting Patterns, Pathogens, and Public Health Risk

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Abstract:

Climate change is changing how emerging infectious diseases (EIDs) spread over the world. The ecological conditions in which diseases, vectors, and hosts interact are changing because of rising temperatures, shifting patterns of rainfall, and increasingly frequent extreme weather events. This narrative review compiles existing research on climate-sensitive infectious illnesses and elucidates the principal mechanisms influencing observed changes. Food- and water-borne illnesses (e.g., cholera, leptospirosis) are increasingly linked to droughts, floods, and disruptions in infrastructure. Vector-borne diseases like dengue, chikungunya, malaria, and Lyme disease are spreading to highland and temperate areas. At the same time, zoonotic spillovers like Ebola, Nipah, and SARS-CoV-2 are happening more commonly in areas where the ecosystem has been altered. New worries are thermotolerant fungal infections and microorganisms that live in permafrost. This review does not offer new epidemiological modelling; instead, it puts recent Global Burden of Disease (GBD) estimates into context. These estimates reveal that the burden of infectious diseases is rising in regions that are sensitive to climate change, including sub-Saharan Africa, South Asia, and Latin America. Weak surveillance systems, health disparities caused by climate change, and broken data streams are some of the biggest gaps in response. Improvements in AI-based forecasting, satellite surveillance, pathogen genomes, and One Health methods provide useful tools for taking action before something happens. It is important to build public health systems that are climate-responsive, transdisciplinary, and fair in order to reduce the growing dangers posed by infectious illnesses connected to climate change.

Keywords: Climate Change; Emerging Infectious Diseases; Vector-Borne Transmission; Zoonotic Spillover One Health Framework

Introduction

Climate change is now universally recognized as both an environmental problem and a serious threat to world health [1]. Anthropogenic increases in greenhouse gas emissions have caused a cascade of ecological changes, including rising global temperatures, changing precipitation patterns, sea-level rise, and an increase in the frequency of extreme weather events. These environmental changes are hastening transitions in the habitats and life cycles of many disease vectors, upsetting ecological balances, and intensifying interactions between humans, animals, and pathogens [2]. As a result, the landscape of infectious illnesses is experiencing rapid and complicated alterations, with previously geographically restricted pathogens spreading into new territory and previously controlled infections resurfacing under novel climatic conditions [3].

Emerging infectious diseases (EIDs) are infections that have recently arrived in a community or are rapidly rising in prevalence or geographical spread. They could be caused by previously unknown pathogens or by existing agents developing new pathogenicity, host range, or resistance profiles. Importantly, the origin and re-emergence of infectious illnesses are becoming more closely related to climate-sensitive dynamics [4]. Vector-borne diseases like malaria and dengue fever, for example, are now showing up in highland and temperate zones that were previously thought to be non-endemic. Waterborne outbreaks of cholera, leptospirosis, and other enteric illnesses are common after floods and natural disasters, while deforestation and changing land use have encouraged the zoonotic spread of viruses such as Ebola, Nipah, and SARS-CoV-2. These patterns highlight the complexities and changing nature of climate-driven infectious hazards [5].

Although understanding of these connections has improved, significant gaps remain in the research. Much of the existing work is still divided by region, disease kind, or disciplinary viewpoint. Few reviews have combined the global scale of climate-related EID dynamics, highlighting novel patterns of emergence, pathogen adaptation, and regional vulnerability. Furthermore, while international organizations have built frameworks for climate-resilient health systems, the translation of climate science into infectious disease preparedness is still unequal and inadequate in many locations, particularly in low- and middle-income nations [6].

While this review does not conduct original interdisciplinary modelling like the formal GBD studies, its findings are consistent with GBD trends showing an increasing proportion of infectious disease burden in regions highly exposed to climate variability (e.g., sub-Saharan Africa, South Asia, and Latin America). Recent GBD estimates confirm a rise in climate-sensitive infectious disease DALYs — particularly vector-borne diseases such as dengue, malaria, and Lyme disease — in geographic areas where temperature and rainfall anomalies have intensified over the past two decades. Our discussion aligns with these trends by synthesizing ecological and epidemiological mechanisms that help explain the burden patterns documented by GBD. Hence, rather than contradicting GBD, our findings contextualize and support GBD observations by providing mechanistic pathways linking climate change to the shifts in infectious disease burden captured in GBD estimates.

This study aims to fill these essential gaps by giving a thorough and up-to-date overview of how climate change is altering the worldwide distribution, dynamics, and risk profile of emerging infectious illnesses.This paper is structured as a *narrative review*, drawing on peer-reviewed literature and global data sources to synthesize current knowledge on climate-sensitive infectious disease trends. Targeted searches were conducted in PubMed, Web of Science, and Scopus using combinations of the keywords *"climate change," "emerging infectious diseases," "vector-borne," "zoonotic," "public health,"* and *"global burden."* Grey literature from global health organizations (e.g., WHO, IPCC, GBD) was also

included. Sources were selected based on their relevance, credibility, and contribution to understanding climate-related disease dynamics and response gaps. No systematic inclusion/exclusion protocol or meta-analysis was employed, in keeping with the integrative nature of a narrative review. We specifically look at the ecological mechanisms by which climate factors promote disease onset, identify key disease categories that are changing, investigate regional trends and hotspots of concern, and assess the current status of public health preparedness. This review intends to guide future research, surveillance tactics, and policy frameworks for anticipating and managing climate-sensitive infectious disease risks by emphasizing current data and incorporating interdisciplinary viewpoints [7].

Methodology

Search Strategy and Selection Criteria: Literature searches were conducted in PubMed, Web of Science, and Scopus using combinations of the keywords "climate change," "emerging infectious diseases," "vector-borne," "zoonotic," "public health," and "global burden." Grey literature from reputable global health organizations (e.g., WHO, IPCC, GBD) was also included.

Inclusion criteria were: (i) peer-reviewed articles or authoritative reports published between 2000 and 2025; (ii) studies that explicitly examined links between climate variables and infectious disease emergence, distribution, or transmission; and (iii) works providing empirical data, modeling, or systematic reviews relevant to climate-sensitive infectious diseases.

Exclusion criteria were: (i) studies without a clear focus on climate–disease interactions; (ii) opinion pieces without supporting data; and (iii) duplicate records across databases.

Climate-Driven Mechanisms of Disease Emergence

Interdisciplinary research that combines climatology, ecology, and epidemiology is shedding new light on the relationship between climate dynamics and infectious disease onset. Climate change disrupts the biological and environmental processes that regulate pathogen transmission, acting as both a catalyst and an amplifier of infectious disease risks. Several climate-sensitive systems play an important role in shaping current and future patterns of disease onset [8].

One of the most obvious and well-documented effects is the impact of temperature and rainfall on vector life cycles. Mosquitoes, ticks, sandflies, and other arthropod vectors are ectothermic creatures whose development, reproduction, and feeding habits are heavily influenced by environmental temperature [9]. Rising global temperatures have increased disease vectors' geographic range and seasonal activity, allowing diseases including malaria, dengue fever, chikungunya, and Lyme disease to spread into previously non-endemic highland and temperate regions. Changes in rainfall patterns, such as increased frequency of heavy precipitation events and protracted droughts, can affect breeding habitats, increasing mosquito multiplication in stagnant water collections and bringing wildlife closer to human settlements during times of water scarcity [10]. Notably, new vector-pathogen connections are emerging, such as Aedes albopictus' adaptation to milder climes, which could indicate an evolutionary shift in vector competence under climatic stress.

Extreme weather phenomena, particularly floods, storms, and droughts, act as acute triggers for infectious disease outbreaks. Flooding not only contaminates water supplies, raising the risk of waterborne diseases like cholera, hepatitis A, and leptospirosis, but it also disrupts health infrastructure and forces people to live in overcrowded, unhygienic shelters. Heatwaves can exacerbate respiratory infections by raising particulate matter and allergen levels, whereas wildfires have been associated with an increase in hospitalizations for viral respiratory disorders [11]. The clustering of epidemics following these events suggests increased pathogen exposure as well as decreased disease control capabilities. Importantly, the temporal association between climate

anomalies and disease outbreaks is becoming more predictable, opening pathways for anticipatory public health interventions [12].

Climate change also fosters disease onset through habitat destruction and zoonotic spillovers. As ecosystems deteriorate due to deforestation, desertification, and agricultural encroachment, which is typically caused by climate-related land degradation, wildlife is forced to interact more closely with human populations [13]. This ecological convergence enhances disease transmission from wildlife reservoirs to human hosts. The advent of SARS-CoV-2, as well as earlier zoonoses like Ebola and Nipah virus, demonstrates the increasingly porous barrier between wildlife and human disease ecologies. Recent research has highlighted the expansion of bat habitats as a result of rising temperatures and changing food availability, raising the potential of bat-borne virus spillovers in new geographic areas [14].

Thawing permafrost and releasing ancient germs is an unexplored but potentially significant frontier. As Arctic and sub-Arctic permafrost melts at a faster rate, long-dormant microorganisms such as viruses, bacteria, and fungal spores may revive. A commonly recognized incident occurred in 2016, when a decades-old anthrax-infected reindeer carcass thawed, resulting in a human outbreak in Siberia [15]. While the full scope of this hazard is unknown, new metagenomic analysis of permafrost cores has revealed viable microbial DNA extending back tens of thousands of years, raising valid concerns about the resurgence of illnesses against which present populations may be immune [16].

Emerging information also points to previously underappreciated illness amplification pathways. These include climate-induced variations in host immunity caused by heat stress and nutritional shortages, microbial evolution in response to environmental stressors, and changes in soil ecology that affect fungal pathogen dynamics [17]. For example, Candida auris, a multidrug-resistant fungus, is thought to have developed as a result of temperature adaptation in reaction to global warming. Toxigenic fungi, such as Aspergillus and Fusarium, also show increased sporulation in response to drought and high temperatures, which has implications for respiratory and foodborne infections [18].

Together, these climate-driven mechanisms highlight the profound and complex ways in which a warming world is changing the global infectious disease landscape. As these processes intensify and overlap, they necessitate proactive, integrated responses based on ecological awareness and predictive surveillance [7]. The intricate interplay of climatic variables, ecological disruption, and infectious disease dynamics can be viewed as a systems-based cascade of interconnected factors. Figure 1 depicts a graphic framework that connects these components and demonstrates how climate change influences public health outcomes via numerous interrelated routes [19].

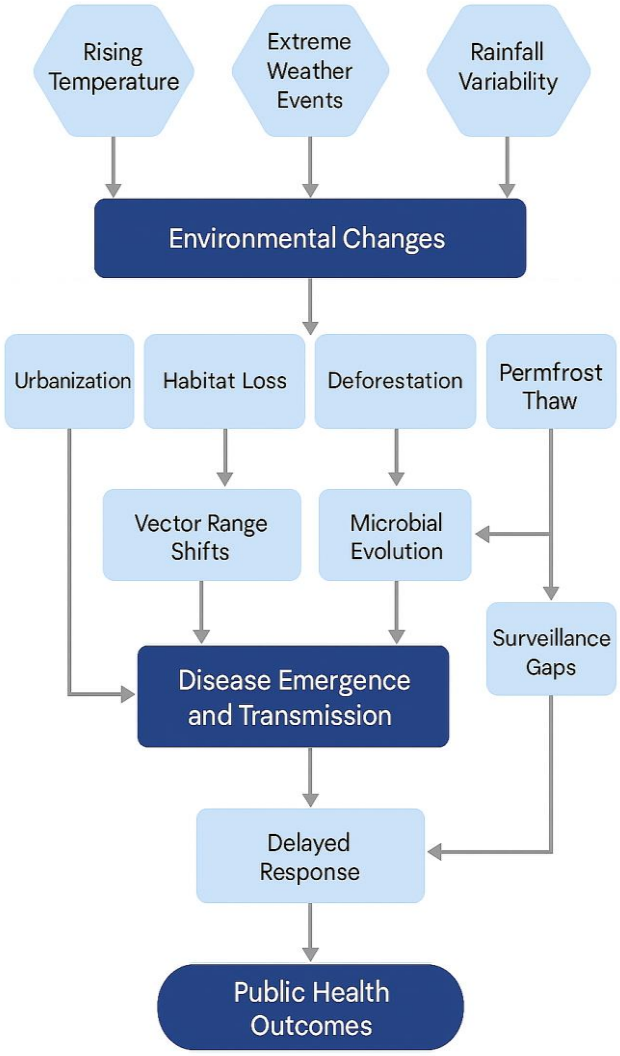

Figure 1. Conceptual Framework: Climate Change as a Driver of Infectious Disease Emergence. This diagram depicts the causal pathways that connect climate drivers—such as temperature rise, rainfall variability, and extreme weather events—to environmental and ecological changes, pathogen dynamics, and, ultimately, public health consequences. Altering vector habitats, displacing wildlife, increasing urban congestion, health disparities, and inadequate surveillance systems are all important intermediate processes.

These combined pressures result in increased epidemic frequency, geographical distribution, and mortality from developing infectious diseases. The framework promotes integrated, system-level thinking in public health preparation and climate adaptation planning.

Changing Patterns of Key Infectious Diseases

Climate change is reshaping vector ecology, water systems, and human-animal interfaces, causing significant changes in the distribution and epidemiology of infectious diseases. This section investigates climate-induced changes in three key categories of infectious diseases: vector-borne, water- and food-borne, and zoonotic spillover events, with a focus on novel geographies, changed seasonality, and developing transmission mechanisms.

Vector-borne Diseases

Vector-borne diseases are among the most vulnerable to climate change, as arthropod vectors such as mosquitoes, ticks, and sandflies rely heavily on environmental temperature, humidity, and rainfall for survival, reproduction, and biting activity. Climate change has significantly altered the geographic and seasonal distribution of numerous major vector-borne diseases, resulting in epidemics in formerly climatically inappropriate places [20].

Malaria, which was formerly confined to tropical and subtropical zones, is now being reported in high-altitude parts of East Africa and South America, where rising temperatures have allowed Anopheles mosquitoes to establish seasonal transmission [21]. The highland regions of Ethiopia and Kenya, for example, have seen episodic spikes in malaria prevalence coincide with unusually warm seasons, a pattern now corroborated by predictive climate-epidemiological models. These developments pose significant risks for immunologically vulnerable individuals and poor health systems in highland areas [22].

Dengue fever, principally transmitted by Aedes aegypti and Aedes albopictus, has rapidly spread throughout Asia, the Americas, and, increasingly, Europe. Dengue fever, long thought to be a tropical disease, is now being recorded on a seasonal basis in southern France, Croatia, and areas of the southern United States [23]. The adaptive migration of Aedes albopictus into temperate areas, enabled by diapause (cold-hardy eggs), demonstrates the vectors' evolutionary adaptability under climate constraints. Furthermore, the expansion of the dengue transmission season, typically by several weeks or months, puts further strain on already overburdened vector-control operations [24].

Chikungunya and Zika virus, which are both spread by Aedes mosquitoes, have followed similar regional expansion trends. Chikungunya outbreaks in Italy and France, as well as the rapid spread of Zika across the Americas in 2015-2016, demonstrate how quickly vector-borne viruses may establish themselves in new climatic zones when ecological and immunological conditions meet. Climate variability has a crucial role in facilitating epidemics, particularly during El Niño periods or warm seasons [25].

Lyme disease, caused by Borrelia burgdorferi and transmitted by Ixodes ticks, has progressively spread in North America and Europe. Warmer winters and longer growing seasons have increased tick survival and host-vector contact, especially in peri-urban and

suburban settings. In Canada, the northern border of Ixodes scapularis has changed several hundred kilometers in the last two decades, and portions of Scandinavia now record endemic transmission zones that were not there in earlier decades [26].

Collectively, these examples illustrate that vector-borne diseases are not only moving geographically but also becoming less predictable in their seasonality and intensity, challenging traditional surveillance frameworks.

Water- and Food-borne Infections

Water- and food-borne diseases are inextricably linked to climatic conditions, including precipitation patterns, flooding, temperature, and water infrastructure reliability. These illnesses are especially frequent in low-resource areas where climate extremes exacerbate existing infrastructure deficiencies.

Cholera, caused by Vibrio cholerae, has a significant link to rising sea surface temperatures, increased rainfall, and coastal flooding—conditions that promote the expansion of planktonic hosts and the contamination of drinking water. El Niño occurrences have been linked to cholera epidemics in the Bay of Bengal and East Africa. Models may predict regional outbreaks weeks ahead using sea surface temperature anomalies. In Haiti, the disastrous 2010 outbreak following an earthquake and flooding demonstrated how climatic and sociopolitical fragilities converge to create epidemic conditions [27].

Typhoid fever, caused by Salmonella enterica serovar Typhi, is still endemic in many parts of South Asia and Sub-Saharan Africa. Flooding occurrences have been associated with an increase in typhoid cases due to overburdened sewage systems and contamination of water sources. At the same time, drought circumstances may result in the concentration of pathogens in stagnant water or the usage of contaminated water sources, as seen in northern Nigeria and southern India [28,29].

Leptospirosis, a zoonotic bacterial infection spread through water polluted with diseased animals' urine, is becoming more well recognized as a climate-sensitive disease. Outbreaks are frequently followed by heavy rainfall and flooding, especially in tropical and subtropical areas with inadequate sanitation and urban drainage systems. Recent research from Brazil, Sri Lanka, and the Philippines has shown that seasonal leptospirosis outbreaks coincide with monsoon rains, and accumulating data suggest that climate change may potentially be altering rodent reservoir dynamics [30].
These diseases exemplify how climate change exacerbates existing water insecurity and sanitation gaps, disproportionately affecting vulnerable populations with limited access to safe water and health care services [31]. Furthermore, they highlight the urgent need for climate-resilient water and sanitation infrastructure as a core component of infectious disease prevention.

Zoonotic and Viral Spillover Events

Climate change is also accelerating the emergence of zoonotic diseases—those transmitted from animals to humans—by increasing human encroachment into wildlife habitats and altering the behavior, distribution, and immune dynamics of both wildlife and domestic animals.

Nipah virus, a bat-borne paramyxovirus discovered in Malaysia in 1998, has resurfaced irregularly in Bangladesh and India, frequently with high case fatality rates [32]. Deforestation and changes in fruiting tree phenology have brought fruit bats closer to human settlements, where viral transmission can occur through contaminated food sources (for example, raw date palm sap) or direct contact. Climate change, which affects food availability and bat roosting habits, is increasingly being linked to the seasonal risk of spillover [33].

Ecological disturbances brought on by hunting, deforestation, and climate irregularities have also been connected to epidemics of the Ebola virus disease in Central and West Africa. Deforestation and landscape have increased human exposure to bat reservoirs [34]. Although little is known about Ebola's zoonotic potential, there is growing evidence that ecosystem stress brought on by climate change may increase the likelihood of future outbreaks [35].

The virus that causes COVID-19, SARS-CoV-2, is a powerful illustration of how anthropogenic factors linked to climate change, such as habitat encroachment, animal trade, and urbanization, can foster the formation of new pathogens [36]. The pandemic has brought attention to the delicate ecological balance that prevents the introduction of high-consequence zoonotic viruses, even though the exact causes are still being investigated [37].

Beyond isolated outbreaks, the global risk environment is currently characterized by a higher frequency of spillovers, partly due to changes in host biodiversity, migration patterns, and pathogen shedding dynamics that are connected to climate change. According to studies, by

fragmentation in Guinea led to an atypical climate during the 2013–2016 West African Ebola epidemic, which may

2070, climate change may cause hundreds of mammal species to move geographically, which could lead to new cross-species viral transmission events[38]. Many of these occurrences could take place in areas with dense populations of people and little surveillance capability.

The significant ecological and epidemiological effects of climate change are reflected in the shifting trends of infectious diseases in these three categories. These changes are qualitative, altering the parameters of risk and necessitating new frameworks for surveillance, readiness, and intervention, in addition to being quantitative in kind, measured in new cases or outbreaks [39]. The diseases that will influence our public health futures will change along with the climate. Figure 2 shows the spatiotemporal distribution of a few high-burden infections over the past few decades, emphasizing important transition zones and new risk areas across regions to illustrate the growing geographic footprint of climate-sensitive infectious illnesses.

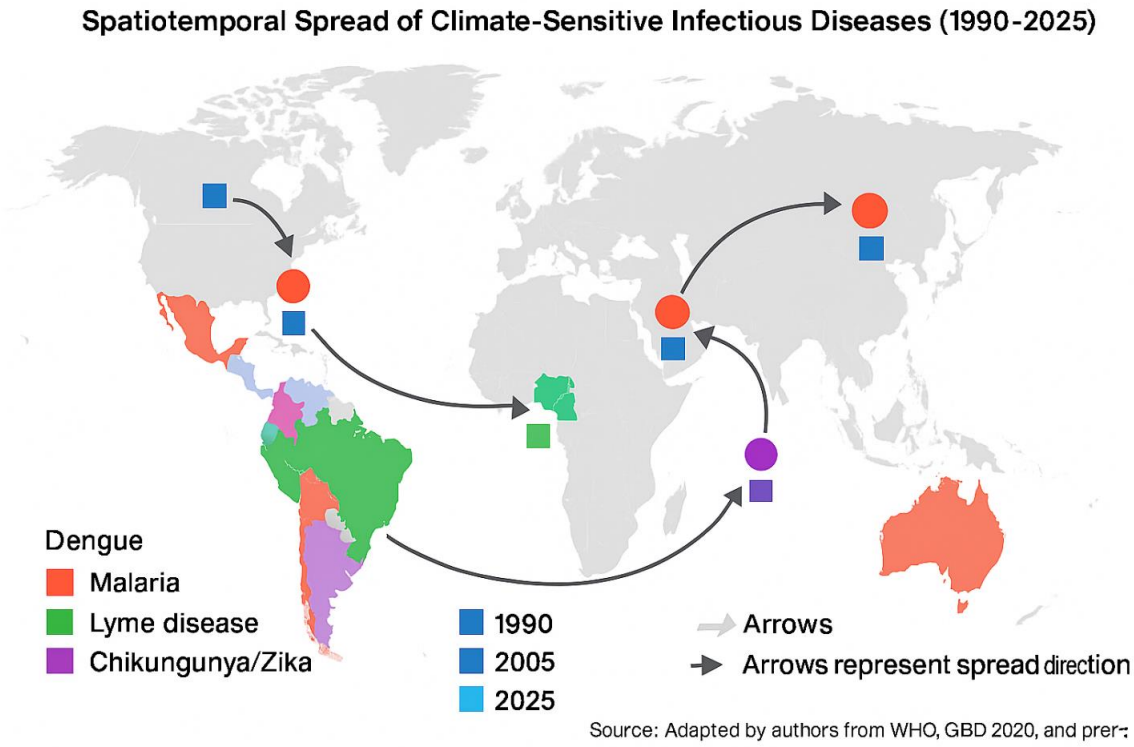

Figure 2 shows how climate-sensitive diseases have spread geographically between 1990 and 2025. From 1990 to anticipated trends in 2025, this choropleth global map shows the chronological and spatial spread of four main climate-sensitive diseases: dengue, malaria, Lyme disease, and chikungunya/Zika. Whereas directional arrows show migration patterns across continents and biological zones, color gradients show the times when diseases first appeared or became more severe. With obvious ramifications for public health readiness in recently impacted areas, the graphic illustrates the poleward and altitudinal changes in disease distribution brought on by warmer temperatures, changed precipitation, and ecological disturbance.

Regional and Global Hotspots

The prevalence of infectious diseases that are impacted by climate change is not distributed equally around the world. Instead, it depicts intricate relationships between regional ecological systems, public health infrastructure, sociopolitical settings, and climatic factors [40]. This section examines major geographic regions where the dangers of infectious diseases caused by climate change are growing, emphasizing emergence and reemergence patterns that indicate both immediate vulnerabilities and more general global trends. Table 1 lists the main EIDs by globe area, principal vector or reservoir, and related climatic determinants to put the spatial variability of climate-sensitive emerging infectious diseases (EIDs) into perspective [41].

Table 1: Climate-Sensitive Emerging Infectious Diseases by Region and Vector.

Climate-Sensitive Emerging Infectious Diseases and Their Main Vectors of Transmission by Region. The main EIDs impacted by climate change are listed in this table, arranged by global region, linked vectors or reservoirs, and climate-related causes (such as rising temperatures, flooding, and changes in land use).

Table 1. Climate-Sensitive Emerging Infectious Diseases by Region and Vector

Region	Disease(s)	Primary Vector/Reservoir	Climate Driver(s)
Sub-Saharan Africa[22]	Malaria, Rift Valley Fever	Anopheles spp., livestock, mosquitoes	Rising temperature, heavy rainfall
Asia-Pacific[30]	Dengue, Leptospirosis, Japanese Encephalitis	Aedes spp., rodents, pigs, Culex spp.	Monsoon variability, urban flooding
The Americas[42]	West Nile Virus, Hantavirus	Birds, mosquitoes, rodents	Drought–flood cycles, warming trends
Europe[43]	Tick-borne Encephalitis, Dengue	Ixodes ticks, Aedes spp	Milder winters, urban heat islands
Arctic/Sub-Arctic[15]	Anthrax (permafrost), ancient microbes	Reindeer, thawed microbes	Permafrost melting

Africa: Malaria Resurgence and Rift Valley Fever

Due to its tremendous ecological diversity, limited ability to adapt, and significant reliance on livelihoods that are dependent on the climate, Africa continues to be one of the most climate-sensitive regions in the

world [44]. Long endemic in sub-Saharan Africa, malaria is making a comeback in highland regions that were previously thought to be transmission-free. Warming temperatures have made it easier for Anopheles mosquitoes to migrate upward in Ethiopia, Uganda, and Kenya, increasing the risk of malaria among high-altitude populations with weak acquired immunity and little ability for surveillance [45]. Tens of millions more people might be exposed to endemic transmission by 2050 if temperatures rise by 1°C, according to climate modeling research [45].

Extreme weather events like El Niño-induced flooding are increasingly linked to Rift Valley Fever (RVF), a zoonotic arboviral illness spread by mosquitoes and exacerbated by livestock. East African outbreaks, such as those in Kenya, Tanzania, and Sudan, have coincided with unusual rainfall patterns that lead to an increase in livestock-human interaction and a jump in mosquito hatching. The connection of climate, health, and food security in the region is highlighted by the resurgence of RVF, which not only endangers human health but also destroys agricultural livelihoods [46].

Asia-Pacific: Leptospirosis, Dengue, and Japanese Encephalitis

Rapid urbanization, monsoonal instability, and dense human-animal-environment interfaces increase the complex web of new infectious disease concerns in the Asia-Pacific area. In flood-prone cities like Manila, Mumbai, and Jakarta, where inadequate drainage and rodent infestation provide the perfect environment for transmission after intense rains, leptospirosis—an often-overlooked bacterial zoonosis—has grown in prevalence. With an increasing yearly frequency in a number of nations, the disease increasingly exhibits seasonal peaks closely associated with climatic trends [47].

In Southeast Asia and the Western Pacific, dengue fever is still spreading rapidly. Aedes mosquito breeding habitats are sporadic due to unpredictable rainfall, and transmission windows have been extended by warming temperatures [48]. Over the past 20 years, annual cases have increased several times in countries like Bangladesh, the Philippines, and Vietnam; these increases are frequently attributed to climatic variability. Due to increased vector suitability and international travel, dengue has resurfaced in Queensland, Australia [49].

Previously unaffected regions, such as the highlands of Nepal and southern China, are now experiencing the spread of Japanese encephalitis (JE), a virus spread by mosquitoes that is prevalent in portions of South and East Asia. This geographic distribution is being aided by changes in the patterns of rice cultivation, the growth of pig farming, and climatic circumstances that favor Culex mosquitoes. Notably, under different warming scenarios, climate models anticipate that JE transmission zones will move northward [50].

The Americas: West Nile Virus and Hantavirus

In both tropical and temperate regions of the Americas, rodent-borne and vector-borne diseases associated with climate change are becoming more prevalent. Since its introduction to the US in 1999, the West Nile Virus (WNV) has spread over most of North America. Longer mosquito breeding seasons and more effective viral replication within vectors have been made possible by warmer temperatures, earlier springs, and fewer frost days [51]. Notably, new research shows that heat waves and drought conditions that draw birds and mosquitoes to areas with dwindling water supplies are associated with the severity and length of WNV epidemics [52].

Climate variations that impact rat population dynamics are increasingly linked to hantavirus pulmonary syndrome (HPS), which is brought on by rodent-borne hantaviruses. Increased rainfall after drought times causes vegetation booms and consequent spikes in rodent hosts like deer mice in the southwestern United States and parts of South America [53]. Usually, human exposure comes next, especially in peri-domestic and rural areas with substandard housing. These patterns highlight how the climate may affect zoonotic reservoir cycles in addition to vector biology.

Europe: Tick-borne Encephalitis and Emerging Arboviruses

Despite its historical temperance, Europe is seeing a continuous rise in infectious diseases that are susceptible to the climate, especially those spread by ticks and

mosquitoes. In Central and Eastern Europe, tick-borne encephalitis (TBE), which is spread by Ixodes ricinus and caused by a flavivirus, is moving northward and higher in elevation. Increased case incidence is a result of warmer winters and milder springs, which improve tick survival and prolong activity periods in nations like Germany, Poland, and the Baltic states [54].

At the same time, new arboviruses, such as dengue, chikungunya, and Zika, are spreading locally over southern Europe, especially in France, Italy, and Spain. Aedes albopictus has established itself in these regions thanks to international trade and climate change adaptability, which has made the environment favorable for occasional outbreaks. The possibility of prolonged arboviral transmission in some regions of Europe is becoming more apparent and less speculative, as climate projections show further warming and increased extreme weather variability [55].

Together, these regional hotspots show that climate change is a geographically distinct phenomenon that alters local disease ecologies in context-specific ways rather than being a uniform or distant hazard. Designing specialized, climate-informed surveillance, control, and public health adaptation methods requires an understanding of these regional dynamics. Therefore, a worldwide response to newly developing infectious diseases needs to be based on local facts, supported by regional realities, and sensitive to the particular vulnerabilities of each hotspot [56].

Public Health Implications and Response Gaps

For public health systems around the world, the expanding relationship between infectious disease development and climate change poses a serious and intricate problem. The institutional ability to identify, decipher, and respond to these signals is still severely limited, despite a growing understanding of the molecular and ecological mechanisms that connect disease and climate. Public health infrastructures, especially those in vulnerable areas, are finding it difficult to keep up with the speed and complexity of new threats as climate-driven disease risks increase in both frequency and extent.

Surveillance Systems Under Pressure

The rapidly changing spatiotemporal dynamics of diseases that are sensitive to climate change are beyond the capabilities of disease monitoring systems, which are already burdened by ongoing underfunding and restricted geographic coverage. Conventional surveillance models, which are intended to identify known infections in known ecological environments, are reactive rather than predictive [7]. These models, however, fall short of capturing the whole picture of new threats as vectors spread to new areas and zoonotic spillovers increase in frequency. For example, the emergence of Anopheles mosquitoes in East African highlands or Aedes albopictus in temperate Europe has often occurred years before official public health acknowledgment, highlighting systemic delays in detection. The use of manual reporting, a lack of laboratory diagnostic capabilities, and a restricted ability to integrate with environmental monitoring data further impair surveillance systems in low- and middle-income countries (LMICs) [57].

Climate Vulnerability and Health Inequities

Marginalized populations—those with the most exposure to climate fluctuation and the least ability to adapt—are disproportionately affected by the public health burden of infectious illnesses that are climate-sensitive. Socioeconomic deprivation and geographic vulnerability frequently coexist, generating a risk feedback loop. Underfunded health systems, subpar housing, restricted access to clean water, and a reliance on climate-sensitive livelihoods (such as agriculture) increase the risk of contracting diseases and suffering serious consequences in sub-Saharan Africa, South Asia, and tiny island states. Additionally, within-country disparities continue to exist: national surveillance and health response systems frequently do not reach Indigenous groups, informal urban settlements, or climate migrants. There is a significant equity gap in the global health response to climate change, as seen by the rarity with which these inequities are addressed in national adaptation strategies [58].

Delays in Outbreak Detection Due to Fragmented Data Systems

The fragmentation of pertinent data streams is one of the most enduring problems in the management of climate-sensitive diseases. Data related to health, weather, ecology, and land use are usually kept apart in different institutional domains with different regulations, formats, and privacy policies [59]. The capacity to create predictive models and send out timely notifications is hampered by this fragmentation. Integration is still uneven, even in wealthy nations with sophisticated digital infrastructure. For instance, the effectiveness of early warning systems for vector-borne outbreaks is restricted by the incompatibility of environmental data platforms and public health reporting systems [60]. The majority of monitoring in LMICs is still done on paper and in retrospect, which slows down reaction times and compromises situational awareness in areas where digital infrastructure may be completely absent.

Challenges in Integrating Climate Models with Public Health Forecasting

Adaptive public health planning is made more difficult by the scientific and methodological differences between epidemiological forecasts and climate modeling. Although climate models are now much better at forecasting trends in temperature, precipitation, and extreme weather, their incorporation into public health decision-making is still in its infancy. While climate scientists frequently create models without direct involvement from health authorities, the majority of public health experts are not trained in interpreting climate data [61]. The co-development of useful technologies suited to the demands of the health industry is hampered by this separation.

Furthermore, nonlinear climate factors, delayed effects, and compounding vulnerabilities like population relocation and malnutrition are frequently overlooked by existing infectious disease forecasting models. For example, real-time data on rainfall variability, vector breeding cycles, and urban infrastructure are rarely included in dengue prediction models, which limits their use in dynamic environments. To close this gap, funding for transdisciplinary cooperation is crucial, especially between academic modelers, health ministries, and meteorological institutes [62].

All things considered, the public health response to infectious diseases brought on by climate change is still reactive, dispersed, and inadequately sensitive to the ecological complexity and social injustice of new threats. Rethinking surveillance as a multisectoral enterprise, integrating equality into preparedness frameworks, and encouraging ongoing, interdisciplinary cooperation across institutions, borders, and data systems are all necessary to meet these problems. The health sector will continue to lag in terms of climate-related disease hazards in the absence of such systemic changes [39].

Innovative Tools and Opportunities

Technological innovation and transdisciplinary frameworks present intriguing pathways for foresight, adaptation, and mitigation as the global health community faces the growing threat of infectious illnesses that are sensitive to climate change. A more proactive and environmentally based approach to disease prevention is being provided by recent developments in artificial intelligence, remote sensing, genomic monitoring, and integrative policy frameworks, which are starting to change the landscape of outbreak prediction, vector control, and pathogen tracking [63].

Real-time predictions of the onset and spread of infectious diseases are increasingly being made using artificial intelligence (AI), big data analytics, and climate modeling [39]. In order to find trends and create prediction risk maps, machine learning algorithms can combine large, diverse datasets, such as satellite observations, weather records, electronic health records, and social media signals. For example, dengue epidemics based on changes in precipitation, humidity, and vector breeding patterns have been significantly predicted by AI-driven models. Early warning systems have been improved in East Africa by combining seasonal climatic forecasts with models of malaria transmission. This has allowed for the more prompt distribution of resources for prevention [64]. However, continuous capacity building in low-resource environments and fair access to data infrastructure are essential for the successful deployment of such technologies.

Vector monitoring has been transformed by satellite imaging and remote sensing technologies, which allow for the real-time tracking of environmental factors

that facilitate the spread of illness. Changes in vegetation, standing water, and urban heat islands—all important markers of mosquito breeding grounds—can be identified with high-resolution photography. By enabling the dynamic detection of new hotspots, these technologies lessen the need for static risk maps [22].

Rift Valley Fever and malaria epidemics are already being predicted in the Sahel and Amazon regions using satellite-derived vegetation indices and surface water models, respectively. When used with geographic information systems (GIS), these tools increase the efficiency of resource allocation and the spatial targeting of vector control efforts [46].

Another revolutionary field that makes it possible to track pathogen evolution, drug resistance, and transmission dynamics in real time is genomic epidemiology. Characterizing epidemics, differentiating between imported and endemic strains, and detecting zoonotic spillover events have all benefited from whole-genome sequencing. Genomic surveillance aided in the quick discovery of new variations during the COVID-19 pandemic and guided international response plans. In the future, combining pathogen genomics with climate-sensitive surveillance systems may offer early warning signs of evolutionary changes brought on by environmental stressors, such as vector-mediated viral recombination or fungal pathogens' adaptability to heat [65].

Lastly, as comprehensive models for comprehending and addressing the interdependencies between environmental, animal, and human health, the One Health and Planetary Health frameworks are becoming more and more popular worldwide. These methods support the breakdown of academic silos and the promotion of cross-sectoral cooperation amongst climatologists, ecologists, veterinarians, and public health professionals. A paradigm change toward more integrated, anticipatory health governance is indicated by the institutionalization of One Health initiatives in national disease control programs, such as those that address zoonotic outbreaks or antibiotic resistance. As the cornerstone of global health security, planetary health highlights the wider ecological boundaries of human growth and calls for structural changes to slow down climate change and biodiversity loss [66].

In sum, these innovative tools and frameworks represent critical opportunities for transforming reactive public health systems into anticipatory, climate-resilient structures. Their effective deployment will require not only technological capacity but also political will, intersectoral coordination, and ethical considerations regarding data equity and access.

Ethical Considerations and Biases

While these tools offer transformative potential, they also raise important ethical concerns. AI-based models may reinforce existing data biases if trained on geographically or demographically incomplete datasets, potentially excluding high-risk but underrepresented populations. Satellite and genomic surveillance raise issues of data privacy, consent, and potential misuse, particularly in low-resource or politically sensitive settings. In addition, the digital divide and unequal access to these technologies can exacerbate global health inequities unless safeguards for data governance, equity, and transparency are integrated into their deployment.

Literature Gaps and Review Limitations

Despite growing research on climate-sensitive infectious diseases, several critical gaps remain in the literature. Much of the current evidence is fragmented by geography, disease type, or disciplinary silo, limiting comprehensive, system-level understanding. There is a lack of longitudinal, high-resolution studies linking specific climate variables to pathogen emergence, particularly in low- and middle-income countries where surveillance data are sparse. Moreover, the interactions between climate change, social determinants of health, and microbial evolution remain underexplored. This narrative review also has several limitations. It does not follow a systematic review protocol, and the selection of literature may reflect some degree of selection bias despite efforts to include high-quality, relevant sources.

Quantitative meta-analysis was not feasible due to variability in study designs and metrics across included sources. Additionally, while this review integrates findings across climatology, public health, and epidemiology, it may not fully capture the breadth of region-specific knowledge published in non-English or local-language sources. These limitations highlight the need for more coordinated, interdisciplinary, and globally inclusive research to better understand and address the climate–infectious disease nexus.

Conclusion and Recommendation

With increasing evidence of changing pathogen ecologies, extending geographic ranges, and changing transmission patterns, climate change is unquestionably changing the worldwide landscape of infectious disease emergence. The upward and poleward migration of vector-borne diseases like Lyme disease, dengue, and malaria; the amplification of waterborne infections after climate extremes; and the increased risk of zoonotic spillovers in ecologically disrupted landscapes are some of the new and underappreciated developments highlighted in this review. Furthermore, a wider reconfiguration of microbial risk under planetary change is indicated by new risks, such as the emergence of fungal species that can adapt to heat stress and the possible release of ancient diseases due to the thawing of permafrost.

The urgent need to create integrated, flexible public health systems that are sensitive to climate cues and quick to react is at the core of these changes. In the face of nonlinear, climate-driven hazards, traditional disease surveillance and forecasting methods—which are limited by sectoral silos and historical baselines—are becoming less and less effective [67]. Though the One Health framework, satellite surveillance, AI-based modeling, and genetic epidemiology are now accessible, their operationalization is still unequal, especially in high-risk and low-resource areas.

We need to develop a radically multidisciplinary paradigm that connects ecology, public health, climate science, and data systems in order to solve the current challenges. Addressing context-specific risks requires regionalized preparedness strategies that are based on local epidemiology and climate data. National and international health initiatives must prioritize strengthening community-based early warning systems, increasing integrated climate-health surveillance, and establishing cross-sectoral collaboration.

High-resolution, longitudinal investigations that connect pathogen dynamics across scales with environmental variables should be given priority in future studies. Equally important are investments in staff training, data integration, and fair access to forecasting tools. Important steps toward sustainable planetary health governance at the policy level include making sure that global climate funding mechanisms specifically take health aspects into account and integrating climate-sensitive illness planning into national adaptation plans [68].

In conclusion, the combination of infectious disease development and climate change is not only a challenge but also an invitation to rethink health security from the perspectives of scientific innovation, environmental resilience, and international solidarity.

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References

1. World Health Organization. Climate change [Internet]. [cited 2025 Jul 16]. Available from: https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
2. Nunes LJR. The Rising Threat of Atmospheric CO2: A Review on the Causes, Impacts, and Mitigation Strategies. Environments. 2023 Apr;10(4):66. https://doi.org/10.3390/environments10040066
3. He Y, Liu WJ, Jia N, Richardson S, Huang C. Viral respiratory infections in a rapidly changing climate: the need to prepare for the next pandemic. eBioMedicine. 2023 May 9;93:104593. https://doi.org/10.1016/j.ebiom.2023.104593
4. Sabin NS, Calliope AS, Simpson SV, Arima H, Ito H, Nishimura T, et al. Implications of human activities for (re)emerging infectious diseases, including COVID-19. J Physiol Anthropol. 2020 Sep 25;39:29. https://doi.org/10.1186/s40101-020-00233-6
5. Alcayna T, Fletcher I, Gibb R, Tremblay L, Funk S, Rao B, et al. Climate-sensitive disease outbreaks in the aftermath of extreme climatic events: A scoping review. One Earth. 2022 Apr 15;5(4):336–50. https://doi.org/10.1016/j.oneear.2022.03.007
6. Issa R, Sarsour A, Cullip T, Toma S, Ruyssen I, Scheerens C. Gaps and opportunities in the climate change, migration and health nexus: Insights from a questionnaire based study. J Migr Health. 2023 Mar 23;7:100171. https://doi.org/10.1016/j.jmh.2023.100171
7. Liao H, Lyon CJ, Ying B, Hu T. Climate change, its impact on emerging infectious diseases and new technologies to combat the challenge. Emerg Microbes Infect. 2024;13(1):2356143. https://doi.org/10.1080/22221751.2023.2356143
8. Piscitelli P, Miani A. Climate Change and Infectious Diseases: Navigating the Intersection through Innovation and Interdisciplinary Approaches. Int J Environ Res Public Health. 2024 Mar;21(3):314. https://doi.org/10.3390/ijerph21030314
9. Adepoju OA, Afinowi OA, Tauheed AM, Danazumi AU, Dibba LBS, Balogun JB, et al. Multisectoral Perspectives on Global Warming and Vector-borne Diseases: a Focus on Southern Europe. Curr Trop Med Rep. 2023;10(2):47–70. https://doi.org/10.1007/s40475-023-00260-9

10. Caminade C, McIntyre KM, Jones AE. Impact of recent and future climate change on vector-borne diseases. Ann N Y Acad Sci. 2019 Jan;1436(1):157–73. https://doi.org/10.1111/nyas.13950
11. Acosta-España JD, Romero-Alvarez D, Luna C, Rodriguez-Morales AJ. Infectious disease outbreaks in the wake of natural flood disasters: global patterns and local implications. Infez Med. 2024;32(4):451–62.
12. Zhao AP, Li S, Cao Z, Hu PJH, Wang J, Xiang Y, et al. AI for science: Predicting infectious diseases. J Saf Sci Resilience. 2024 Jun 1;5(2):130–46. https://doi.org/10.1016/j.jssr.2024.05.004
13. Wegner GI, Murray KA, Springmann M, Muller A, Sokolow SH, Saylors K, et al. Averting wildlife-borne infectious disease epidemics requires a focus on socio-ecological drivers and a redesign of the global food system. eClinicalMedicine. 2022 Apr 18;47:101386. https://doi.org/10.1016/j.eclinm.2022.101386
14. Agusi ER, Allendorf V, Eze EA, Asala O, Shittu I, Dietze K, et al. SARS-CoV-2 at the Human–Animal Interface: Implication for Global Public Health from an African Perspective. Viruses. 2022 Nov 9;14(11):2473. https://doi.org/10.3390/v14112473
15. Yarzábal LA, Salazar LMB, Batista-García RA. Climate change, melting cryosphere and frozen pathogens: Should we worry…? Environ Sustain (Singap). 2021;4(3):489–501. https://doi.org/10.1007/s42398-021-00197-w
16. Imberti L, Tiecco G, Logiudice J, Castelli F, Quiros-Roldan E. Effects of Climate Change on the Immune System: A Narrative Review. Health Sci Rep. 2025 Apr 18;8(4):e70627. https://doi.org/10.1002/hsr2.7062
17. Pfenning-Butterworth A, Buckley LB, Drake JM, Farner JE, Farrell MJ, Gehman ALM, et al. Interconnecting global threats: climate change, biodiversity loss, and infectious diseases. Lancet Planet Health. 2024 Apr;8(4):e270. https://doi.org/10.1016/S2542-5196(24)00049-5
18. Mojahed N, Mohammadkhani MA, Mohamadkhani A. Climate Crises and Developing Vector-Borne Diseases: A Narrative Review. Iran J Public Health. 2022 Dec;51(12):2664–73.
19. Masse RS, Vythilingam I, Fornace K, Othman H, Liu X, Jaafar AJ, et al. Impact of environmental factors on the bionomics of Anopheles mosquito vectors of zoonotic malaria: A narrative review. One Health. 2025 Jul 14;101141. https://doi.org/10.1016/j.onehlt.2024.101141
20. Lühken R, Brattig N, Becker N. Introduction of invasive mosquito species into Europe and prospects for arbovirus transmission and vector control in an era of globalization. Infect Dis Poverty. 2023 Nov 30;12(1):109. https://doi.org/10.1186/s40249-023-01128-7
21. Delrieu M, Martinet JP, O'Connor O, Viennet E, Menkes C, Burtet-Sarramegna V, et al. Temperature and transmission of chikungunya, dengue, and Zika viruses: A systematic review. Curr Res Parasitol Vector Borne Dis. 2023 Aug 24;4:100139. https://doi.org/10.1016/j.crpvbd.2023.100139
22. Couper LI, MacDonald AJ, Mordecai EA. Impact of prior and projected climate change on US Lyme disease incidence. Glob Chang Biol. 2021 Feb;27(4):738–54. https://doi.org/10.1111/gcb.15432
23. Usmani M, Brumfield KD, Jamal Y, Huq A, Colwell RR, Jutla A. A Review of the Environmental Trigger and Transmission Components for Prediction of Cholera. Trop Med Infect Dis. 2021 Aug

5;6(3):147. https://doi.org/10.3390/tropicalmed6030147

24. Kaljee LM, Pach A, Garrett D, Bajracharya D, Karki K, Khan I. Social and Economic Burden Associated With Typhoid Fever in Kathmandu and Surrounding Areas: A Qualitative Study. J Infect Dis. 2018 Nov 10;218(suppl_4):S243–9. https://doi.org/10.1093/infdis/jiy479
25. Folorunsho S. The Role of Social Determinants of Health in Shaping Racial and Disability Disparities Among Older Adults in the United States. J Aging Soc Policy. 2025;1–17. https://doi.org/10.1080/08959420.2025.2329841
26. Bradley EA, Lockaby G. Leptospirosis and the Environment: A Review and Future Directions. Pathogens. 2023 Sep 16;12(9):1167. https://doi.org/10.3390/pathogens12091167
27. Folorunsho S, Ajayi V, Sanmori M, Suleiman M, Abdullateef R, Abdulganiyu A. Access to and Utilization of Dental Care Services by Older Adults in Nigeria: Barriers and Facilitators. Spec Care Dentist. 2025;45(3):e70040. https://doi.org/10.1111/scd.70040
28. Hauser N, Gushiken AC, Narayanan S, Kottilil S, Chua JV. Evolution of Nipah Virus Infection: Past, Present, and Future Considerations. Trop Med Infect Dis. 2021 Feb 14;6(1):24. https://doi.org/10.3390/tropicalmed6010024
29. Poirier O, Castañeda RR de, Bolon I, Ray N. Modelling forest degradation and risk of disease outbreaks in mainland Equatorial Guinea. J Public Health Emerg. 2021 Jun 25;5(0). Available from: https://jphe.amegroups.org/article/view/7288
30. Elechi KW, Igboaka CD, Tiamiyu BB, Ugbor MJE, Arthur C, Ezeh OM, et al. Phytochemical Screening of Ficus globosa Latex (Moraceae) as a Source of Novel Antimicrobial Compounds. Path Sci. 2025 Mar 31;11(3):9001–10. https://doi.org/10.22178/pos.1103-2
31. Hemmeda L, Shabani MM, Kolawole BO, Muhammad SA, Fatima K, Siddiqui A, et al. Third wave of COVID-19 pandemic in Africa: Challenges and recommendations. Ann Med Surg. 2022 Aug;80. Available from: https://journals.lww.com/annals-of-medicine-and-surgery/fulltext/2022/08000/third_wave_of_covid_19_pandemic_in_africa_.189.aspx
32. Carlson CJ, Albery GF, Merow C, Trisos CH, Zipfel CM, Eskew EA, et al. Climate change increases cross-species viral transmission risk. Nature. 2022 Jul;607(7919):555–62. https://doi.org/10.1038/s41586-022-04788-w
33. Lawal OP, Igwe EP, Olosunde A, Chisom EP, Okeh DU, Olowookere AK, et al. Integrating Real-Time Data and Machine Learning in Predicting Infectious Disease Outbreaks. Asian J Microbiol Biotechnol. 2025 May;10(1):147–63. https://doi.org/10.9734/ajmob/2025/v10i1203
34. Folorunsho S, Ajayi V, Abdulrazaq O. Juvenile delinquency as a contemporary issue in Nigeria. Afr J Soc Issues. 2024 Mar 23;7(1):116–32. https://doi.org/10.5281/zenodo.10920064
35. McMichael AJ, Woodruff RE. Climate change and infectious diseases. In: Mayer KH, Pizer HF, editors. The Social Ecology of Infectious Diseases. San Diego: Academic Press; 2008. p. 378–407. Available from: https://www.sciencedirect.com/science/article/pii/B9780123704665500194
36. D'Amore C, Grimaldi P, Ascione T, Conti V, Sellitto C, Franci G, et al. West Nile Virus diffusion in temperate regions and climate change. Infez Med. 2023 Mar 1;31(1):20–30.
37. Adepoju OA, Afinowi OA, Tauheed AM, Danazumi AU, Dibba LBS, Balogun JB, et al. Multisectoral Perspectives on Global Warming and Vector-borne Diseases. Curr Trop Med Rep. 2023;10(2):47–70. https://doi.org/10.1007/s40475-023-00260-9

38. Ezhova E, Orlov D, Suhonen E, Kaverin D, Mahura A, Gennadinik V, et al. Climatic Factors Influencing the Anthrax Outbreak of 2016 in Siberia, Russia. Ecohealth. 2021;18(2):217–28. https://doi.org/10.1007/s10393-021-01531-4
39. Aik J, Ong J, Ng LC. The effects of climate variability and seasonal influence on diarrhoeal disease in Singapore. Int J Hyg Environ Health. 2020 Jun 1;227:113517. https://doi.org/10.1016/j.ijheh.2020.113517
40. Ryan SJ, Lippi CA, Zermoglio F. Shifting transmission risk for malaria in Africa with climate change. Malar J. 2020 May 1;19:170. https://doi.org/10.1186/s12936-020-03259-1
41. Ndishimye P, Umuhoza T, Umutoni B, Zakham F, Ndayambaje M, Hewins B, et al. Rift Valley Fever outbreaks in the East African Community. Front Public Health. 2024 Dec 11;12:1298594. https://doi.org/10.3389/fpubh.2024.1298594
42. Hassell JM, Begon M, Ward MJ, Fèvre EM. Urbanization and Disease Emergence: Dynamics at the Wildlife–Livestock–Human Interface. Trends Ecol Evol. 2017 Jan;32(1):55–67. https://doi.org/10.1016/j.tree.2016.09.012
43. Jamal MK, Sanaei B, Naderi M, Past V, Abadi SHA, Khazaei R, et al. Investigating the recent outbreak of dengue fever in Iran. Egypt J Intern Med. 2025 Feb 18;37(1):37. https://doi.org/10.1186/s43162-025-00224-9
44. Sah R, Mohanty A, Rohilla R, Asija A, Sedhai YR, Chandran D, et al. Japanese encephalitis prevalence and outbreaks in Nepal. Int J Surg. 2023 Mar 3;110(10):6822. https://doi.org/10.1016/j.ijsu.2023.106822
45. Beermann S, Dobler G, Faber M, Frank C, Habedank B, Hagedorn P, et al. Impact of climate change on vector- and rodent-borne infectious diseases. J Health Monit. 2023 Jun 1;8(Suppl 3):33.
46. Wang HR, Liu T, Gao X, Wang HB, Xiao JH. Impact of climate change on West Nile virus and adaptation responses. Infect Dis Poverty. 2024 May 24;13(1):38. https://doi.org/10.1186/s40249-024-01174-5
47. Douglas KO, Payne K, Sabino-Santos G, Agard J. Influence of Climatic Factors on Human Hantavirus Infections in Latin America and the Caribbean. Pathogens. 2021 Dec 23;11(1):15. https://doi.org/10.3390/pathogens11010015
48. El-Sayed A, Kamel M. Climatic changes and their role in emergence and re-emergence of diseases. Environ Sci Pollut Res Int. 2020;27(18):22336–52. https://doi.org/10.1007/s11356-020-08764-6
49. Kraemer MUG, Reiner RC Jr, Brady OJ, Messina JP, Gilbert M, Pigott DM, et al. Past and future spread of Aedes aegypti and Aedes albopictus. Nat Microbiol. 2019 Mar 4;4(5):854. https://doi.org/10.1038/s41564-019-0376-y
50. Muluneh MG. Impact of climate change on biodiversity and food security: A review. Agric Food Secur. 2021 Sep 6;10(1):36. https://doi.org/10.1186/s40066-021-00325-y
51. Liao H, Lyon CJ, Ying B, Hu T. Climate change, its impact on emerging infectious diseases and new technologies to combat the challenge. Emerg Microbes Infect. 2024;13(1):2356143. https://doi.org/10.1080/22221751.2023.2356143
52. Martins FP, Paschoalotto MAC, Closs J, Bukowski M, Veras MM. The Double Burden: Climate Change Challenges for Health Systems. Environ Health Insights. 2024 Nov 20;18:11786302241298789. https://doi.org/10.1177/11786302241298789
53. Lawal O, Oyebamiji HO, Kelenna IJ, Chioma FJ, Oyefeso E, Adeyemi BI, et al. A Review on

Usage of Digital Health Literacy to Combat Antibiotic Misuse in Nigeria. J Pharma Insights Res. 2025 Apr 5;3(2):258–69.

54. Onwuemelem LA, Orobator ET, Onyedum NN, Chibueze ES, Kanu I, Christopher AA, et al. Molecular Mechanisms of Clonal Hematopoiesis in Age-Related Cardiovascular Disease. J Pharma Insights Res. 2025 Apr 5;3(2):358–72.
55. Hess JJ, McDowell JZ, Luber G. Integrating Climate Change Adaptation into Public Health Practice. Environ Health Perspect. 2011 Oct 13;120(2):171. https://doi.org/10.1289/ehp.1103515
56. Thiede BC, Strube J. Climate Variability and Child Nutrition: Findings from Sub-Saharan Africa. Glob Environ Change. 2020 Nov;65:102192. https://doi.org/10.1016/j.gloenvcha.2020.102192
57. Lawal OP, Egwuatu EC, Akanbi KO, Orobator ET, Eweje OZ, Omotayo EO, et al. Fighting Resistance With Data: Leveraging Digital Surveillance in Nigeria. Path Sci. 2025 Mar 31;11(3):1009–17. https://doi.org/10.22178/pos.1103-3
58. Ayomide IT, Promise LO, Christopher AA, Okikiola PP, Esther AD, Favour AC, et al. The Impact of Antimicrobial Resistance on Co-INFECTIONS. Int J Pathogen Res. 2024 Nov 29;13(6):117–28.
59. Pronyk PM, Alwis R de, Rockett R, Basile K, Boucher YF, Pang V, et al. Advancing pathogen genomics in resource-limited settings. Cell Genomics. 2023 Nov 17;3(12):100443. https://doi.org/10.1016/j.xgen.2023.100443
60. Hobusch U, Scheuch M, Heuckmann B, Hodžić A, Hobusch GM, Rammel C, et al. One Health Education Nexus. Front Public Health. 2024 Mar 22;11:1337748. https://doi.org/10.3389/fpubh.2023.1337748
61. Lawal O, Elechi K, Adekunle F, Farinde O, Kolapo T, Igbokwe C, et al. A Review on Artificial Intelligence and Point-of-Care Diagnostics in Nigeria. J Pharma Insights Res. 2025 Apr 5;3(2):166–75.
62. Oseghale ID, Lawal OP, Ubebe DO, Orjiewulu VC, Igunma AA, Odey OP, et al. Ethnomedicinal and Phytopharmacological Aspects of Vernonia amygdalina. Asian J Res Biochem. 2024 Oct 14;14(6):41–57. https://doi.org/10.9734/ajrb/2024/v14i62403

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Review Article

Strengthening Preparedness for Infectious Disease Outbreaks in Sub-Saharan Africa: Lessons from Recent Outbreaks

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Abstract:

One of the major public health emergencies that has affected lives globally is infectious disease outbreaks. These issues are of great concern due to their potential to transcend borders. The control and management of such outbreaks even with the attention channelled towards it globally has been a difficult task in many developing and underdeveloped countries of the world of which the majority of sub-saharan african countries fall under. However, with this review, we aim to contribute to the body of knowledge dedicated towards control of infectious diseases by analyzing the preparedness of Sub-Saharan African (SSA) countries in managing infectious disease outbreaks based on lessons from recent outbreaks (with focus on COVID-19, Lassa fever and Ebola outbreaks). In carrying out this narrative review, we make use of PubMed and African Journals Online (AJOL) as the primary literature sources. To ensure we capture publications from reputable organizations that are solely involved in control of infectious diseases in the region, we carried out a grey literature search.

However in this review, we synthesized challenges such as weak healthcare systems, inadequate healthcare infrastructure, inefficient surveillance systems, poor data management and reporting practices, limited laboratory capacity and reliance on external donors for supplies during emergencies.

The review proposes potential interventional measures aimed at addressing these challenges aimed at enhancing the preparedness

The findings from this review provide critical insights into the preparedness gaps and potential interventions, informing policy and practice to enhance the region's resilience future outbreaks.

Keywords: Infectious Disease Outbreaks; Sub-Saharan Africa; Public Health, Healthcare Systems; Laboratory Capacity; Community Engagement; Surveillance Systems; Data Management; Supply Chain Management

Introduction

The world has been challenged by several unforeseen events that are life threatening of which health emergencies such as infectious illness outbreaks are one of them. Infectious disease outbreaks are a major and ongoing global health problem, and especially a great challenge to many developing and underdeveloped countries due to their unsophisticated healthcare systems [1]. Many infectious diseases outbreaks have been witnessed in Sub-Saharan African (SSA) countries and these have a great impact on lives and economy [2]. Notable among these infectious disease outbreaks witnessed in this part of the world were the Ebola outbreak crisis, the ongoing issues of Lassa fever, and the COVID-19 pandemic. However, the control and management of these outbreaks in many SSA nations is challenged by a lack of healthcare infrastructure, poor public health preparedness, and limited budget which often led to delay in response, thereby worsening the impact of these outbreaks [3].

These epidemics had a big throw on both the economy and have led to loss of lives. The Ebola outbreak in West Africa from 2014 to 2016, resulted in over 28,600 cases and more than 11,000 deaths [4]. On the other hand, the Lassa fever outbreaks have been reoccurring and there are between 100,000 and 300,000 reported new cases per year, and about 5,000 people die from the disease yearly with the average case fatality rate of hospitalized being 15% [5, 6]. Moreover, the economic impact of the Ebola outbreak is between $30 billion and $50 billion, which was a big problem for the affected countries, like Guinea, Liberia, and Sierra Leone [7].

The COVID-19 pandemic made the deficiencies of healthcare systems in this region more evident as countries in SSA faced challenges of limited medical supplies, ventilators, and personal protective equipment (PPE) during the pandemic, thereby making it difficult for them to handle the crisis efficiently [8, 9, 10]. One of the main reasons these problems exist is that many SSA countries' healthcare systems are underfunded The World Bank (2022) pointed out that healthcare expenditure in SSA was only 5% of GDP on average, which is far lower than the African Union's (AU) estimated 15% recommended to ensure healthcare system improvement [11, 12, 13].

Nevertheless, in addressing infectious diseases outbreak it is very important that healthcare systems at all levels be ready at all times as these outbreaks do not give prior notice before occurring. There is also a need for continuous assessment of preparedness level of healthcare systems. Prior studies have discussed the need for frameworks or measures to examine whether health system investments have made countries more prepared for natural disasters or health emergencies. Researchers and health organizations have defined and quantified the complicated concepts of preparedness, vulnerability, and resilience to infectious disease outbreaks and other emergencies to aid policy design and decision-making [14].

The ongoing process of predicting disaster situations, preventing or mitigating bad outcomes, and creating capacities and resources to respond to and recover from them is called preparedness [15]. Public health systems, healthcare organizations, employers or corporations, academic institutions, communities, and individuals are key players required to demonstrate these capacities or acquire resources for certain forms of readiness [16]. Preparation may include improving disease detection and investigation systems, creating outbreak response plans, and distributing human, material, and financial resources to support public health infrastructure and ensure adequate response [17].

Objective

The aim of this review is to synthesize findings from publications on previous infectious diseases outbreaks (COVID-19, lassa fever, and Ebola) preparedness in Sub-Saharan African countries.

Methodology

Narrative synthesis approach was adopted in this review to assess the preparedness of Sub-Saharan African nations towards infectious disease outbreak. PubMed and African Journals Online (AJOL) were the primary databases consulted for this review. To ensure more comprehensive search, grey literature search was conducted in reputable sources like the African Union (AU), the World Health Organization (WHO), and the Centers for Disease Control and Prevention (CDC) that feature publications on infectious disease outbreaks in SSA countries. The search focused on Ebola, Lassa fever, and COVID-19 outbreaks and preparedness articles from 2010 to search date (June 20, 2025). The search terms employed were "Ebola outbreak", "COVID-19

outbreak", "Lassa fever outbreak", "infectious disease outbreaks","Sub-Saharan Africa", "readiness", and "preparedness". The goal was to synthesize findings from publication on infectious disease readiness in Sub-Saharan Africa, concentrating on healthcare systems, surveillance systems, laboratory capacities, data management, and community involvement. Publications published in English-language were included. However, only peer-reviewed academic papers from reputable organizations mentioned above were included. Papers not published between 2010 and the search date were excluded.

Narrative Synthesis

This section is structured around key themes identified in the literature on infectious disease preparedness in Sub-Saharan Africa, categorized under the following headings.

Recent Outbreaks Epidemiology

Sub-Saharan African countries have witnessed several infectious disease outbreaks including Zika, Cholera, monkey pox Rift valley fever, COVID-19, Lassa fever, Ebola virus etc. The scope of this review focuses on recent outbreaks such as Ebola virus, COVID-19 and Lassa fever. Although there was a relatively low number of reported cases of COVID-19 in Sub-Saharan Africa at the very onset of the pandemic but as it spread globally the number of cases rapidly intensified, resulting in 7,926,999 reported cases (representing 3.6% of worldwide cases) and 200,045 fatalities (4.4% of overall global fatalities recorded) by September 7, 2021 [18]. However, among the Sub-Saharan African countries, South Africa was the most affected, followed by Ethiopia, Kenya, and Nigeria. During the COVID-19 pandemic Sub-Saharan African countries encountered significant obstacles, especially regarding testing, contact tracing, and case management [19]. Several studies have discussed some of these obstacles as evident in Epée et al. (2022) study in which Cameroon's strategy for epidemic control was examined and emphasized the importance of proactive measures to address some of the obstacles encountered such as mass testing, border control, and early quarantine. However, the effectiveness of these measures is dependent on the country's capacity to swiftly mobilize resources and execute coordinated policies [20].

On the other hand, the Ebola virus disease (EVD) which is the most significant outbreak that occurred between 2014 and 2016, led to over 28,600 reported cases and more than 11,000 deaths with a case fatality ratio of 28% to 75% [21]. Among the Sub-saharan African countries, the Democratic Republic of Congo (DRC), Sierra Leone, Liberia, and Guinea were the countries that were mostly affected. However, of all EVD infections recorded from 2001 to 2025, the DRC accounted for 46% of all EVD infections. There are many species of Ebora virus, however, the Zaire virus happened to be the most predominant during these outbreaks followed by the Sudan virus [22]. The outbreak rapidly spread as a result of delayed response which is linked to lack of cooperation among governments and international institutions and inefficient surveillance systems. However, countries like Nigeria demonstrated a more effective control of the outbreak through prompt response measures and significant community involvement [23].

Nevertheless, Lassa Fever which is a viral hemorrhagic fever prevalent in West African countries including Nigeria, Liberia, Sierra Leone, and Guinea still exists in some of these West countries [5, 6], with estimated annual incidence ranging from 100,000 to 300,000 cases, and approximately 5,000 deaths recorded each year [24]. For hospitalized patients with severe cases of the disease, the case fatality rate is 15% [24]. Recent outbreaks, notably in Nigeria, have been significant, with major outbreaks witnessed in 2016 and 2018. Lassa fever epidemics may not have gotten as much attention around the world as Ebola or COVID-19, but they have a big impact on local populations and healthcare systems that should not be ignored. These outbreaks keep happening, and they are getting worse because of poor surveillance and limited healthcare resources. This puts a lot of stress on health systems in the affected regions [24].

Preparedness of Healthcare Systems

The recent outbreaks have exerted considerable strain on healthcare systems across Sub-Saharan Africa, highlighting the essential need for ongoing investments in health infrastructure and workforce development. As noted by Asamani et al. (2024), Sub-Saharan Africa is experiencing a significant shortfall in healthcare personnel, projected to reach a deficit of 6.1 million health workers by the year 2030 [25]. The current shortage presents a considerable obstacle to effective outbreak response, given that healthcare facilities frequently operate with insufficient staffing and limited resources [25]. According to Ahmat et al. (2022), countries such as Sey-

chelles, Namibia, Mauritius, and South Africa made notable advancements in fortifying healthcare systems in 2019, particularly regarding the increase in healthcare professionals and the improvement of service delivery, as illustrated in Figure 1. Nonetheless, numerous other nations continue to have insufficient health infrastructure [26]. Conversely, the latest evaluation (2021-2024) revealed that merely 7 countries in Africa (Libya, Eswatini, Tunisia, Mauritius, Seychelles, Algeria, and Cape Verde) achieved the doctors-patient ratio of 10 doctors per 10,000 citizens. The primary factors contributing to progress in these nations include heightened investments in healthcare, the integration of emerging technologies, and international collaborations [27].

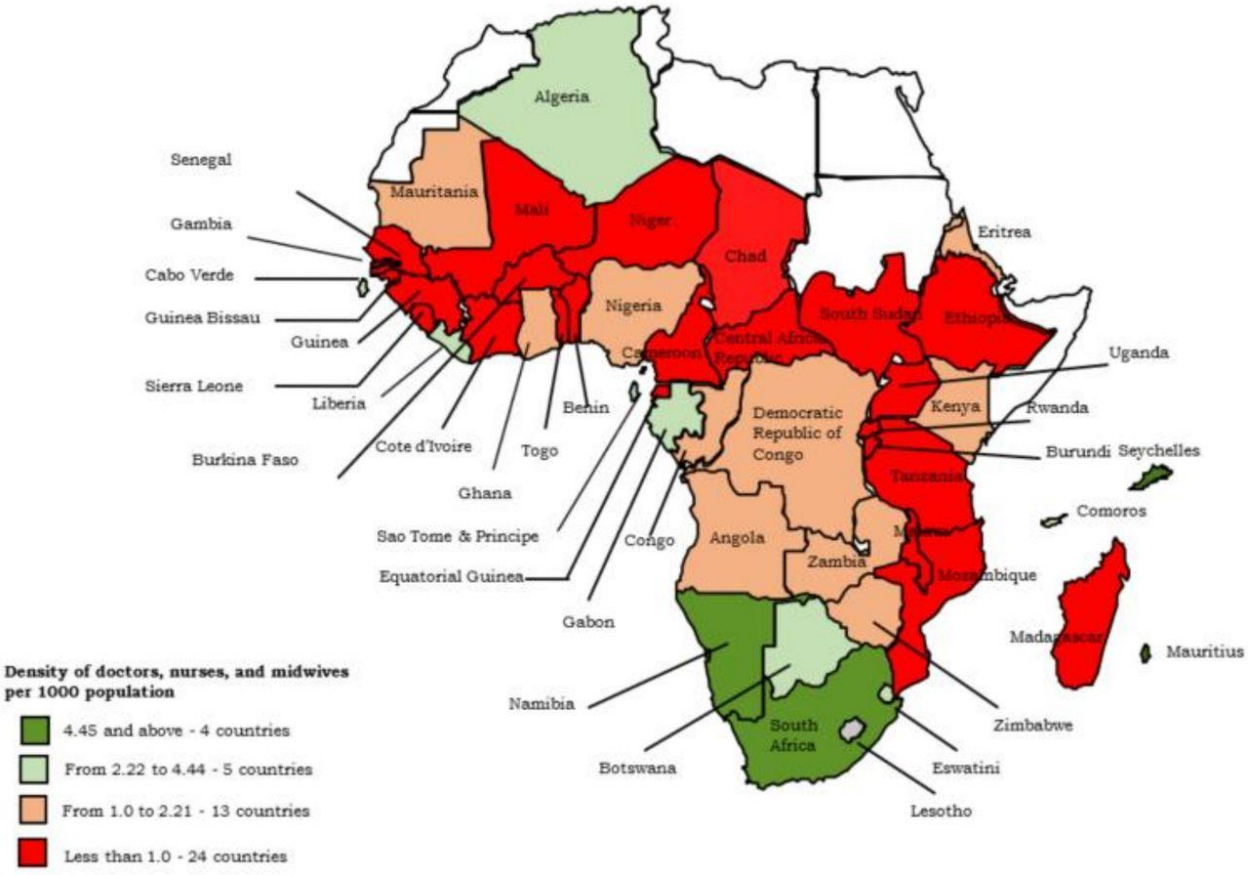

Figure 1: The density of Available Healthcare Professionals per 1,000 Population in Africa as at 2019. (Source: Ahmat et al., 2022 [26])

In terms of preparedness assessment, Salami et al. (2022) highlighted that healthcare systems in nations such as Nigeria and Sierra Leone were not adequately prepared for large-scale outbreaks, largely attributable to insufficient infrastructure and inadequately equipped health facilities [28]. Moreover, the African Health Security Index (AHSI) assessment stipulated that no African country is fully ready to deal with potential pandemic or epidemic risks as African countries face different problems relating to building strong healthcare systems, keeping up investments and adequate competences, as well as improving health security governance [29]. Therefore, several countries in SSA had low scores on preparation measures, such as access to healthcare, the capability of health systems, and how quickly they could respond to emergencies.

However, several factors have been highlighted in the literature that are linked to challenges of achieving optimal preparedness such as insufficient use of the existing healthcare workforce, attributed to inadequate training and a lack of continuous professional development [30]. Additionally, the challenges of ineffective governance and political turmoil were found to significantly hinder response to infectious disease outbreaks in Sub-Saharan Africa, thereby leading to delay in response and in some cases fragmented efforts [31]. Moreover, the majority of countries in the region have unsophisticated surveillance systems, which hinder early detection and swift response, thereby leading to rapid spread of outbreaks and at the longrun loss of lives and a strain on the economy [32].

In the same vein, the events during the COVID-19 pandemic shed light on the preparedness of healthcare systems SSA countries. For example, the region found

it difficult accessing vaccines at first, as less than 20% of the population were vaccinated by early 2023 [33]. However, according to the Africa-Europe Foundation (2022), Africa has only 3% of the world's healthcare workers, even though it has a disproportionately high number of diseases [34]. This was also evident during the COVID-19 pandemic. Another issue encountered during the pandemic was inefficient data management and reporting systems, this makes it difficult to track, and respond to disease outbreaks [35]. Despite these notable efforts and contributions of bodies such as the African Union and the World Health Organization (WHO) at both national and international levels during the pandemic and beyond were evident through their several initiatives to make healthcare systems more resilient [36, 37].

countries continued to have difficulty with diagnosis [43].

Laboratory and Technological Readiness

The availability and the number of efficient laboratories plays a crucial role during infectious diseases outbreaks and it is one of the metrics of preparedness [38]. However, establishing enduring and dependable laboratory networks throughout the region is quite challenging, particularly in rural areas where access to healthcare services and diagnostic technology is limited [39]. The WHO EVD Togo Report (2014) emphasizes the critical need for enhancing laboratory infrastructure in Sub-Saharan Africa to facilitate prompt disease diagnosis and effective treatment [40]. However, in terms of technology, Asiri et al. (2023) examined the application of modern technologies such as artificial intelligence (AI) driven diagnosis and automations in improving laboratory efficiency and found out that the application these technologies varies significantly throughout SSA region, often due to financial constraints and insufficient local technical expertise [41].

Findings from several studies have highlighted the laboratory and technological aspect of preparedness. Golin et al. (2020) demonstrated that the absence of diagnostic facilities during the Ebola and COVID-19 outbreaks significantly impeded the ability of the affected countries to respond promptly [42]. Iyare et al. (2023) conducted a study demonstrating how technological advancements, such as the Internet of Medical Things (IoMT), could enhance the preparedness of laboratories in Sub-Saharan Africa and facilitate monitoring of outbreaks [23]. However, in a study by Erike et al. (2024) who examined the IoMT-enabled monitoring systems implementation, it was concluded that integrating these technologies into health systems will significantly enhance the ability to monitor and respond to future epidemics [21].

On the other hand, a survey of African Union Member States by Ashenafi et al. (2024) revealed significant variability in the testing capacity in SSA regions. According to the survey results, some of the most significant issues were the lack of sufficient or relevant testing reagents, not having enough qualified staff, and lack of sufficient infrastructure [43]. During the COVID-19 pandemic, these problems were clear because many

Community Involvement and Public Health Infrastructural Development

Public health infrastructural development and community engagement are integral parts of control, management and interventional measures of infectious disease, both of which are crucial for preparedness. However, in the healthcare systems of SSA there have been reports of poor infrastructural development and limited public health communication networks due to drawbacks in familiarity of modern technology and computer literacy [44]. In a study by Niyigena et al. (2023) in which the impact of community health workers in Rwanda's response to COVID-19 were discussed, it was found that they play a crucial role in disseminating accurate information and advocating for preventive measures [45].

Moreover, the findings of Owoyemi et al. (2021) shows that engaging the community in health education, monitoring, and service provision has played a crucial role in mitigating the impacts of past epidemics such as Ebola and COVID-19 [46]. Additionally, community-based surveillance systems approach, enable local communities to be solely involved in interventional plans as they take an active role in the monitoring and reporting of diseases, thereby enhancing prompt response [46].

However, in terms of preparedness, the lack of sufficient community involvement during the Ebola outbreak in Sierra Leone resulted in opposition to public health measures, such as quarantine and safe burial practices according to Gebremeskel et al. (2021) [20]. Moreover, in many SSA nations, inadequate public health infrastructure and insufficient coordination among government agencies and international organizations persistently hinder the region's ability to effectively manage and control diseases [47].

Surveillance and Data Management

In identification and prevention of infectious disease outbreaks, there is a need for monitoring and data management systems that are efficient. According to WHO (2019) countries with robust surveillance systems were more capable of timely response to COVID-19 which helps in mitigating spread of the outbreak [48]. Nonetheless, the management of data in SSA countries is challenged by a lot of factors such as inadequate data quality, poor technology, and insufficient training for health professionals in data collection and analysis [24]. These are evident based on the findings from the review by Mremi et al. (2021), which stipulated that despite advancements in surveillance systems, numerous countries continue to face challenges in obtaining comprehensive data as Health management information systems (HMIS) usually serve as the primary data source [32].

However, in many SSA countries, the effectiveness of the HMIS is often compromised due to poor data quality as well as omission of data [32]. In order to address such data issues, mobile technologies, event-focused surveillance that supports real-time data correction and community-driven monitoring can be collectively employed to improve traditional data management methods [50]. Moreover, big data analytics and artificial intelligence (AI) can be employed to help enhance predictive models for infectious disease outbreaks [32].

Despite significant advancements, the persistent challenge lies in achieving collaboration among data gathering initiatives across various sectors, such as health, agriculture, and weather, to establish a cohesive and integrated surveillance system. Enhancing data integration and coordinating responses across various diseases and sectors necessitates the establishment of comprehensive surveillance systems that encompass a broad spectrum of sectors and indicators [32].

Furthermore, effective data generation is crucial for enhancing surveillance and reaction to infectious disease outbreaks. By leveraging digital health technologies, mobile apps, and other data collection methods, healthcare systems can gather timely and accurate data on disease trends, transmission patterns, and outbreak dynamics. Integration of data from various sectors, such as health, agriculture, and weather, can facilitate a more comprehensive understanding of outbreak risks and enable evidence-based decision-making. For instance, climate data can inform predictive models for vector-borne diseases, while agricultural data can help identify potential animal-human transmission interfaces. Strengthening data generation and integration capabilities can ultimately enable more effective preparedness and response strategies in Sub-Saharan Africa.

Supply Chain Management

Management of the supply chains for medical products in Sub-Saharan Africa presents significant challenges. The WHO (2019) and World Bank (2025) emphasized the critical role of regional supply chains in the rapid distribution of essential medical supplies, such as vaccinations, PPE, and pharmaceuticals, to areas in need during outbreaks [48, 49]. Salami et al. (2022) indicated that the disruptions caused by the COVID-19 pandemic highlighted the deficiencies in Africa's supply chains. A coordinated plan that incorporates both international and local partners is essential for enhancing their strength [28].

The Africa CDC (2025) demonstrates that a robust supply chain requires the ability to forecast demand, establish procurement agreements, and manage logistics effectively. It is essential to conduct regular simulation exercises to ensure preparedness [49]. To ensure rapid responses during emergencies, maintaining the integrity of cold chain infrastructure and strategically stockpiling at key locations is essential. The pandemic highlighted the deficiencies in delivery systems, underscoring the critical need for robust regional frameworks capable of managing various outbreaks effectively. The Africa CDC's framework emphasizes the importance of having pre-existing agreements to enhance the speed of responses during health emergencies [50].

Summary of Lessons from Recent Outbreaks

Events of the recent infectious disease outbreaks in Sub-Saharan Africa such as the COVID-19 pandemic, the Ebola outbreak, and the Lassa fever outbreak sheds light on some of the obstacles associated with public health interventions execution during health emergencies. Notable among these obstacles was weak healthcare systems, as there were lack of medical supplies as well as lack of healthcare workers and laboratory inefficiencies reported. On the other hand, a number of nations, particularly those experiencing conflict or political instability, encountered challenges related to delayed responses, attributed to inadequate management and coordination efforts.

Nonetheless, there remains a continuous necessity for enhancement in aspects such as improved data management, more effective monitoring systems, and increased professional training for healthcare workers.

Countries such as South Africa that invested in robust surveillance systems demonstrated greater effectiveness in managing outbreaks. Mremi et al. (2021) indicate that the application of digital technologies for real-time data collection and predictive modelling has the potential to enhance the management of outbreaks [32].

Figure 2 below highlights the critical factors to consider when preparing for and responding to an outbreak of an infectious disease.

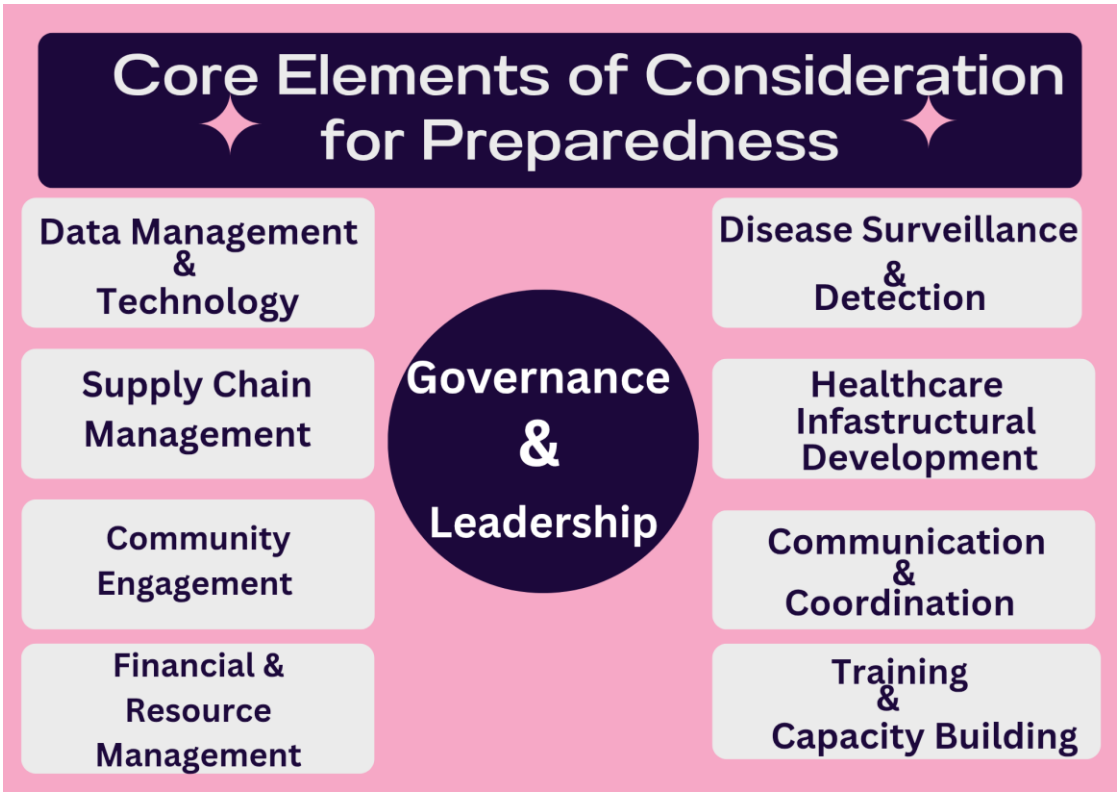

Figure 2: The Core Elements of Consideration for Infectious Disease Outbreak Response and Preparedness

Conclusion

The findings of this study shows there are still some aspects of preparedness metrics that many SSA countries need to pay attention to, such as strengthening healthcare systems, investing in infrastructural development and healthcare workforce, as well as digital health technologies, improving laboratory capacity, and optimizing surveillance mechanisms in Sub-Saharan Africa. Furthermore, it is essential for governments to enhance collaboration with international partners to secure sustainable funding and allocate resources effectively for preparedness initiatives.

Specifically, nations should prioritize ongoing professional development for healthcare professionals dedicated to infectious disease outbreaks to ensure they are ready and capable of handling such emergencies. Moreover, it should be ensured that reliable diagnostic systems, and supply chains are efficient in order to increase local capacity for controlling epidemics. National response strategies must also incorporate community engagement and public participation at all levels of healthcare (primary, secondary and tertiary levels), as these are vital in adhering to public health protocols during outbreaks.

Based on this review, the summary of the major challenges and possible interventional measures that will help improve infectious disease preparedness in Sub-Saharan Africa are contained in Table 1.

Table 1: Sub-Saharan Africa Infectious Disease Preparedness Challenges and Interventions

Preparedness Challenge	Suggested Intervention
Weak Healthcare Systems	Strengthen healthcare infrastructure by increasing investments in healthcare facilities, workforce training, and resources.
Limited Laboratory Capacity	Enhance laboratory systems by improving diagnostic capabilities, integrating mobile diagnostic tools, and building regional laboratory networks.
Inadequate Public Health Infrastructure	Improve public health infrastructure by expanding facilities, ensuring access to medical supplies, and enhancing emergency management systems.
Poor Surveillance and Data Systems	Develop robust surveillance systems by integrating digital health technologies for real-time data collection, reporting, and sharing.
Reliance on External Support	Build local capacity for self-sufficiency by investing in local production of medical supplies and creating sustainable funding mechanisms for healthcare.
Inadequate Community Engagement	Foster community involvement by developing public health education campaigns and empowering local leaders to facilitate health interventions.
Insufficient Supply Chain Management	Improve local supply chain management by strengthening logistics systems, creating regional supply hubs, and ensuring timely distribution of critical medical resources.

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References

1. Hassan HK, Adigun OA, Manirambona E, et al. Mitigating the escalating threat of infectious diseases outbreaks in tropical Africa: a perspective examination of challenges and strategies for future preparedness. Beni-Suef Univ J Basic Appl Sci. 2024;13:55. https://doi.org/10.1186/s43088-024-00511-y
2. Umviligihozo G, Mupfumi L, Sonela N, Naicker D, Obuku EA, Koofhethile C, et al. Sub-Saharan Africa preparedness and response to the COVID-19 pandemic: a perspective of early career African scientists. Wellcome Open Res. 2020;5:163.
3. Moyo E, Mhango M, Moyo P, Dzinamarira T, Chitungo I, Murewanhema G. Emerging infectious disease outbreaks in Sub-Saharan Africa: Learning from the past and present to be better prepared for future outbreaks. Front Public Health. 2023;11:1049986. https://doi.org/10.3389/fpubh.2023.1049986
4. World Health Organization. Ebola outbreak 2014-2016 - West Africa: Overview [Internet]. Geneva: WHO; [cited 2025 Jun 12]. Available from: https://www.who.int/emergencies/situations/ebola-outbreak-2014-2016-West-Africa
5. Africa CDC. Lassa Fever [Internet]. Addis Ababa: Africa CDC; [cited 2025 Jun 12]. Available from: https://africacdc.org/disease/lassa-fever/
6. World Health Organization. Lassa fever; 5 December 2024 [Internet]. Geneva: WHO; 2024 [cited 2025 Jun 12]. Available from: https://www.who.int/news-room/fact-sheets/detail/lassa-fever
7. Obeng-Kusi M, Martin J, Abraham I. The economic burden of Ebola virus disease: a review and recommendations for analysis. J Med Econ. 2024;27(1):309–23. https://doi.org/10.1080/13696998.2024.2313358
8. Kawuki J, Chan PS, Fang Y, Chen S, Mo PKH, Wang Z. Knowledge and practice of personal protective measures against COVID-19 in Africa: systematic review. JMIR Public Health Surveill. 2023;9:e44051. https://doi.org/10.2196/44051
9. Dubbink JH, Branco TM, Kamara KB, et al. COVID-19 treatment in sub-Saharan Africa: If the best is not available, the available becomes the best. Travel Med Infect Dis. 2020;37:101878. https://doi.org/10.1016/j.tmaid.2020.101878
10. Uwaezuoke SN. Strengthening health systems in Africa: The COVID-19 pandemic fallout. J Pan Afr Thorac Soc. 2020;1(1):15–9. http://dx.doi.org/10.25259/JPATS_14_2020
11. World Bank. Current health expenditure (% of GDP) - Sub-Saharan Africa [Internet]. Washington, D.C.: The World Bank; [cited 2025 Jun 14]. Available from: https://data.worldbank.org/indicator/SH.XPD.CHEX.GD.ZS?locations=ZG
12. Piatti-Fünfkirchen M, Lindelow M, Yoo K. What are governments spending on health in East and Southern Africa? Health Syst Reform. 2018;4(4):284-99. https://doi.org/10.1080/23288604.2018.1510287
13. Jowett M, Brunal MP, Flores G, Cylus J. Spending targets for health: no magic number. Geneva: World Health Organization; 2016 Jan 20 [cited 2025 Jun 14]. Available from: https://iris.who.int/handle/10665/250048
14. Kaiser M, Chen AT, Gluckman P. Should policy makers trust composite indices? A commentary on the pitfalls of inappropriate indices for

policy formation. Health Res Policy Syst. 2021;19(1):40. https://doi.org/10.1186/s12961-021-00702-4

15. World Health Organization. A strategic framework for emergency preparedness. Geneva: WHO; 2017. Available from: https://www.who.int/publications/i/item/a-strategic-framework-for-emergency-preparedness
16. Leinhos M, Qari SH, Williams-Johnson M. Preparedness and emergency response research centers: using a public health systems approach to improve all-hazards preparedness and response. Public Health Rep. 2014;129(Suppl 4):8-18. https://doi.org/10.1177/00333549141296S403
17. Fatiregun AA, Isere EE. Epidemic preparedness and management: A guide on Lassa fever outbreak preparedness plan. Niger Med J. 2017;58(1):1-6. https://doi.org/10.4103/0300-1652.218414
18. Eghosa F. African nations meeting WHO's doctor-to-population ratio (2000-2024). Intelpoint. 2025 Mar 24 [cited 2025 Jun 20]. Available from: https://intelpoint.co/blogs/african-nations-who-doctor-ratio-2000-2024/
19. Alimi Y, Wabacha J. Strengthening coordination and collaboration of one health approach for zoonotic diseases in Africa. One Health Outlook. 2023;5(1):10. https://doi.org/10.1186/s42522-023-00085-2
20. Gebremeskel AT, Otu A, Abimbola S, Yaya S. Building resilient health systems in Africa beyond the COVID-19 pandemic response. BMJ Glob Health. 2021;6(6):e006108. https://doi.org/10.1136/bmjgh-2021-006108
21. Erike AI, Ikerionwu CO, Mshelia YU, Elei FO. Internet of medical things (IoMT) enabled third-party monitoring model for infectious diseases control during epidemics. Niger J Technol. 2024;43(2). https://doi.org/10.4314/njt.v43i2.18
22. Mbachu CO, Ekenna AC, Agbawodikeizu UP, Onwujekwe O. Role and use of evidence in health system response to COVID-19 in Nigeria: a mixed method study. Pan Afr Med J. 2023;44:191. https://doi.org/10.11604/pamj.2023.44.191.38990
23. Iyare O, Saidu S, Umeokonkwo CD, Okedo-Alex IN, Mba SC, Olorukooba AA. Lassa fever prevention in Nigeria: A study of a multi-disciplinary mix of healthcare workers in a referral treatment centre in Nigeria. J Interv Epidemiol Public Health. 2023;6(1). Available from: https://www.afenet-journal.net/content/article/6/10/full
24. Gueye AS, Okeibunor J, Ngofa R, Conteh I, Onyeneho N, Mbainodji N, et al. Willingness of WHO staff to work in health emergencies in the African Region: opportunity for phased deployment of staff and ensure continuity of health services. Pan Afr Med J. 2024;47:68. https://doi.org/10.11604/pamj.2024.47.68.40362
25. Asamani JA, Bediakon KS, Boniol M, Munga'tu JK, Akugri FA, Muvango LL, et al. Projected health workforce requirements and shortage for addressing the disease burden in the WHO Africa Region, 2022–2030: a needs-based modelling study. BMJ Glob Health. 2024;7(Suppl 1):e015972. https://doi.org/10.1136/bmjgh-2024-015972
26. Ahmat A, Okoroafor SC, Kazanga I, Asamani JA, Millogo JJ, Illou MM, et al. The health workforce status in the WHO African Region: findings of a cross-sectional study. BMJ Glob Health. 2022;7(Suppl

1):e008317. https://doi.org/10.1136/bmjgh-2021-008317

27. Eghosa F. African nations meeting WHO's doctor-to-population ratio (2000-2024). Intelpoint. 2025 Mar 24 [cited 2025 Jun 20]. Available from: https://intelpoint.co/blogs/african-nations-who-doctor-ratio-2000-2024/
28. Salami KA, Mandi HE, Imbault N, Tornieporth NG. The promise, problems, and pitfalls of including pregnant women in clinical trials of Lassa fever vaccine: a qualitative assessment of sub-Sahara Africa investigators' perception. Pan Afr Med J. 2022;41:242. https://doi.org/10.11604/pamj.2022.41.242.33863
29. Africa Health Security Index [Internet]. [cited 2025 Jun 15]. Available from: https://ghsindex.org/africa-health-security-index/
30. Epée E, Mandeng N, Libwea JN, Mouangué C, Belinga S, Fokam J, et al. Two years of Cameroon's resilient response to the COVID-19 pandemic. J Cameroon Acad Sci. 2022;18:493-500. Available from: https://www.ajol.info/index.php/jcas/article/view/237717
31. Meena P, Abdellatif D, Tiwari V, Chatterjee S, Luyckx VA. Health systems preparedness for infectious disease outbreaks: relevance for nephrology. Semin Nephrol. 2023;43(5):151465. https://doi.org/10.1016/j.semnephrol.2023.151465
32. Mremi IR, George J, Rumisha SF, et al. Twenty years of integrated disease surveillance and response in Sub-Saharan Africa: challenges and opportunities for effective management of infectious disease epidemics. One Health Outlook. 2021;3:22. https://doi.org/10.1186/s42522-021-00052-9
33. Wollburg P, Markhof Y, Kanyanda S, et al. The evolution of COVID-19 vaccine hesitancy in Sub-Saharan Africa: evidence from panel survey data. BMC Proc. 2023;17(Suppl 7):8. https://doi.org/10.1186/s12919-023-00266-x
34. The Africa-Europe Foundation. Health – Addressing the health workforce crisis in Africa and in Europe [Internet]. 2022 Nov 10 [cited 2025 Jun 15]. Available from: https://www.africaeuropefoundation.org/stories/health-addressing-the-health-workforce-crisis-in-africa-and-in-europe/
35. Achieng MS, Ogundaini OO. Big data analytics for integrated infectious disease surveillance in sub-Saharan Africa. South Afr J Inf Manag. 2024;26(1):a1668. https://hdl.handle.net/10520/ejc-info_v26_n1_a1668
36. Alimi Y, Wabacha J. Strengthening coordination and collaboration of one health approach for zoonotic diseases in Africa. One Health Outlook. 2023;5(1):10. https://doi.org/10.1186/s42522-023-00085-2
37. World Bank. Africa Centres for Disease Control receives a $100 million boost from the World Bank to strengthen continental public health preparedness [Internet]. Washington, D.C.: The World Bank; 2022 Jul 21 [cited 2025 Jun 18]. Available from: https://www.worldbank.org/en/news/press-release/2022/07/21/africa-centres-for-disease-control-receives-a-100-million-boost-from-the-world-bank-to-strengthen-continental-public-hea
38. EisBrenner T, Tipples G, Kuschak T, Gilmour M. Laboratory response checklist for infectious disease outbreaks—preparedness and response considerations for emerging threats. Can Commun Dis Rep. 2020;46(10):311-9. https://doi.org/10.14745/ccdr.v46i10a01

39. Musuka H, Mano O, Iradukunda PG, Pierre G, Munyonho FT, Moyo E, et al. Global health development aid initiatives and the quality of medical laboratory services in sub-Saharan: a narrative review. Glob Health J. 2025 Jun 8. https://doi.org/10.1016/j.glohj.2025.06.006
40. World Health Organization (WHO). Togo: Ebola preparedness strengthening team country visit, 24 November–1 December 2014. Geneva: WHO; 2014 [cited 2025 Jun 20]. Available from: https://www.who.int/publications/i/item/WHO-EVD-PCV-Togo-14
41. Asiri AI, Al Mutlaq AA, Al Faqeer AAH, Al Ahmari SS, Al Hefthi AAAH, Al Zahrani AA. Enhancing laboratory capacities and pandemic preparedness: A critical evaluation of global strategies and approaches. IJRDO - J Health Sci Nurs. 2023;9(7):45–52. Available from: https://www.ijrdo.org/index.php/hsn/article/view/5978
42. Golin R, Godfrey C, Firth J, Lee L, Minior T, Phelps BR, et al. PEPFAR's response to the convergence of the HIV and COVID-19 pandemics in Sub-Saharan Africa. J Int AIDS Soc. 2020;23(8):e25587. https://doi.org/10.1002/jia2.25587
43. Ashenafi A, Sule O, Peter T, Mashate S, Otieno O, Kebede A, et al. Diagnostics for detection and surveillance of priority epidemic-prone diseases in Africa: an assessment of testing capacity and laboratory strengthening needs. Front Public Health. 2024;12:1438334.
44. Khatri RB, Endalamaw A, Erku D, Wolka E, Nigatu F, Zewdie A, et al. Preparedness, impacts, and responses of public health emergencies towards health security: qualitative synthesis of evidence. Arch Public Health. 2023;81(1):208. https://doi.org/10.1186/s13690-023-01223-y
45. Niyigena A, Nyirahabimana N, Cubaka V, Mukandayisenga V, Ngizwenayo E, Niyigena PC, et al. Knowledge and practices surrounding outbreaks and COVID-19 among community health workers in rural Rwanda: a cross-sectional mixed-methods study. Pan Afr Med J. 2023;45:35. https://doi.org/10.11604/pamj.2023.45.35.37020
46. Owoyemi A, Okolie EA, Omitiran K, Amaechi UA, Sodipo BO, Ajumobi O, et al. Importance of community-level interventions during the COVID-19 pandemic: lessons from Sub-Saharan Africa. Am J Trop Med Hyg. 2021;105(4):879-83. https://doi.org/10.4269/ajtmh.20-1533
47. Zhao F, Kovacevic R, Bishai D, Weintraub J, editors. Strategic investment for health system resilience: A three-layer framework. Washington, D.C.: World Bank; 2024 [cited 2025 Jun 20]. Available from: https://documents1.worldbank.org/curated/en/099623011052446919/pdf/IDU122ce063d1da0c14d271b08d18d75d51511e4.pdf
48. World Health Organization (WHO). Integrated disease surveillance and response technical guidelines, booklet four: Sections 8 and 9. WHO/AF/WHE/CPI/02.2019. Geneva: WHO; 2019 [cited 2025 Jun 20]. Available from: https://iris.who.int/bitstream/handle/10665/312364/WHO-AF-WHE-CPI-02.2019-eng.pdf
49. The World Bank. Health security program in Western and Central Africa, using the multi-phase approach - Phase 2 (P508833) Project Information Document (PID) Concept Stage. Report No: PIDDC01177. Washington, D.C.: The World Bank; 2025 Mar 18 [cited 2025 Jun 20]. Available

from: https://documents1.worldbank.org/curated/en/099031825231064077/pdf/P508833-ac25b1d5-b8c6-40a9-b07d-3fa69f7f57ea.pdf

50. Africa Centres for Disease Control and Prevention. Framework for supply chain management for public health emergency preparedness and response [Internet]. Addis Ababa: Africa CDC; [cited 2025 Jun 20]. Available from: https://africacdc.org/download/framework-for-supply-chain-management-for-public-health-emergency-preparedness-and-response/

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Review Article

Towards Universal Health Coverage in Kazakhstan from the Alma-Ata Declaration in 1978 to Astana Declaration in 2018: Challenges, Successes and Future Outlook

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Abstract:

For centuries, health was viewed from the lens of biomedicine as the core. This view considered medical professionals and hospitals as the sole agents and venues where health could be obtained, with only passive mentions of the impact of social determinants of health. In a paradigm shift from this view in 1978, at the Alma-Ata Declaration in Kazakhstan, 134 member countries of the WHO formalized the recognition of the social determinants of health into a global policy. Factors such as accessibility, affordability, availability, social and economic status, and education about health services are crucial for population health. The Alma-Ata Declaration required the governments of member countries to include deliberate policies that strengthen and promote population health, by ensuring that social measures are included in their national development plans while recognizing the rights of collective and individual participation of their populations. The phrase "Primary Health Care" (PHC) was then adopted. It was defined as "essential health care based on practical, scientifically sound and socially acceptable methods which are of relevant technology, made accessible and affordable to families and communities through their participation". Health became a human right underpinned by equity and population participation principles. The aftermath of the Declaration was an immediate implementation challenge. It was soon to be realized that PHC interventions are not linear and generalizable like biomedical interventions which have specific measures and predictable outcomes. To date, there is no blueprint for universal intervention measures because economic disparities, social and situational contexts differ and determine the success of any intervention measure. Our review explores the challenges and successes of the implementation of PHC in Kazakhstan, the birthplace of the global health policy on PHC.

Keywords: PHC; Universal Health Coverage; Kazakhstan

Introduction

Kazakhstan is the country that saw the birth of the modern concept of primary health care (PHC) with the declaration of Alma-Ata, adopted at an International Conference in what was then the capital city of the Kazakh Soviet Republic (now Almaty) in 1978. The Alma-Ata Declaration defines PHC as essential health care based on practical, scientifically sound, and socially acceptable methods and technology. It emphasizes making healthcare universally accessible to individuals and families in the community at a cost that the community and country can afford, and therefore a key to achieving universal health coverage (UHC) [1].

PHC requires a comprehensive approach that includes not only treatment of diseases but also prevention, promotion, curative and rehabilitative care. A core principle of the Alma-Ata Declaration is the pursuit of equity, emphasizing that health is a fundamental human right and that inequity in the provision of healthcare services is unacceptable. Equal access, particularly for marginalized and vulnerable populations, is a critical component of PHC. The Declaration advocates for the involvement of local communities in decision-making to ensure that health services meet their needs and priorities. It also recognizes that health is influenced by multiple sectors and calls for collaboration across various sectors such as education, agriculture, housing, and public works to address the broader determinants of health.

The Alma-Ata Declaration has had a profound impact on global health policies and strategies. It inspired the Astana Declaration on Primary Health Care (PHC) in October 2018 at the Global Conference on Primary Health Care in Astana, the current capital of the Republic of Kazakhstan. The conference emphasized the foundational principles of the 1978 Alma-Ata Declaration, and reaffirmed global commitment to strengthen PHC as a central element to achieving UHC in line with the Sustainable Development Goals (SDGs), and outlined the strategic framework for countries to develop their PHC systems, ultimately aiming to achieve better health outcomes and greater health equity[1].

In the Soviet period, the Semashko system emerged as a cost-efficient and highly organized model of healthcare. It was built on a centralized, hospital-oriented framework, featuring a hierarchical structure in which the state both financed and delivered medical services free of charge to the population. A strong focus was placed on the prevention and management of infectious diseases such as tuberculosis and typhus, with both primary care and hospitals forming the backbone of the system. This approach enabled notable achievements, including reliable access to vaccines, widespread immunization coverage, and reductions in infant and maternal mortality[2].

After the collapse of the USSR, however, Kazakhstan's health sector faced serious difficulties. Many facilities lacked adequate equipment, medicines, and up-to-date technologies. As a result, the newly independent republic inherited a hospital network that was oversized, underfunded, and inefficient, which made large-scale reforms of public healthcare unavoidable.

Since independence, Kazakhstan has been making significant strides in improving its PHC system. As a country in transition in the aftermath of the independence, Kazakhstan faced multiple health challenges such as low life expectancy, high infant and maternal mortality, surging rates of non-communicable disease (NCD), high rates of infectious diseases such as tuberculosis, and the emerging threat of HIV/AIDS. The situation was worsened by the lack of an adequate number of skilled health workforce and imbalances in healthcare facility staffing compounded by the initial economic downtime after the independence. The country was still struggling to optimally achieve the health-system-level outcomes of the Alma-Ata Declaration made on its soil just over a decade earlier. Citizens still expected to see a specialist as first-line consultation when ill and building trust in a PHC system remained a challenge[3]. The economic situation began to improve in the second half of the 1990s. As the country's GDP neared 10%, the next twenty years saw major reforms aimed at building multidisciplinary, team-oriented primary healthcare. This process was supported by improvements in governance, human and physical resources, financing, and the digital transformation of PHC. More recently, the country has adopted a mandatory social health insurance system, which was aimed to greatly enhance access to healthcare services.

The objective of this Review is to describe the development of the PHC systems in Kazakhstan, describe its current status and challenges, and reflect on future prospects.

Methods

We searched PubMed using the following terms: care, primary health; primary health care; primary healthcare; primary care; physician; family practice; general practice; general practice physician; ambulatory care, and Kazakhstan. We also searched web pages of international organizations like the World Health Organization and the Organization for Economic Cooperation and Development (OECD) to find relevant documents describing PHC in Kazakhstan, its situation, progress, and challenges. Titles and abstracts were reviewed by 4 authors to determine their relevance to the objective of this review (ASS, NMT, KY and UK).

Results

Implementation and Successes

As the host of the 1978 Alma-Ata Declaration, Kazakhstan initiated its first steps toward putting the principles of primary health care into practice, maintaining this progress until the dissolution of the Soviet Union in 1990. Following independence, the country's PHC system advanced significantly; however, as this study will demonstrate, greater emphasis is still required to ensure the system achieves outcomes that make a lasting impact.

Kazakhstan, covering 2,773,000 km² and home to about 20 million people, holds the distinction of being the world's largest landlocked nation and one of the least densely populated. Following independence, the country underwent significant political, economic, and social reforms, with the oil and gas industry playing a central role in driving its rapid economic expansion. Today, Kazakhstan is characterized by a relatively youthful population and a changing demographic structure. In 2023, its Gross Domestic Product (GDP) was valued at approximately USD 261.4 billion[4].

Kazakhstan undertook a series of phased healthcare reforms aimed at enhancing service availability, improving efficiency, and ensuring equitable access for the population. The process began with the State Program for Reforming and Developing Healthcare (2005–2010), which laid the groundwork for subsequent initiatives. This was followed by the "*Salamatty Kazakhstan"* program (2011–2015)[5], the "*Densaulyk"* program (2016–2020), and most recently, the State Program for the Development of Healthcare of the Republic of Kazakhstan for 2020–2025[6].

Since the launch of the mandatory social health insurance system in 2018, healthcare financing in Kazakhstan has relied on pooled funds drawn from two main sources: the republican budget, covering socially vulnerable groups such as children, the elderly, pregnant women, and the unemployed through tax revenues, and contributions from employers and employees directed to the Social Health Insurance Fund[7]. Although the scope of publicly financed services is fairly broad, out-of-pocket spending remains significant. Citizens and permanent residents are entitled to two main packages of medical services: the State-Guaranteed Basic Package, funded by the government, and the Social Health Insurance Package[8]. Both are administered by the Social Health Insurance Fund, which acts as the sole public purchaser of healthcare services.

At the PHC level in Kazakhstan, the range of services covers: (i) screening and diagnostic measures for early identification of diseases; (ii) outpatient medical care; and (iii) inpatient substitutes such as day hospitals and home-based treatment; (iv) evaluation of temporary disability; (v) regular preventive health examinations; (vi) immunization; (vii) activities promoting healthy lifestyles and providing counseling; (viii) guidance on balanced nutrition; (ix) family planning services; (x) maternal and childbirth care; and (xi) health status monitoring.

PHC in Kazakhstan is centered on accessibility and quality. Nearly 6,000 PHC organizations (polyclinics), 23,000 physicians, and 63,000 nurses provide services nationwide. Special attention is given to preventive care, with extensive programs for child health, school health posts, and regular screenings for adults. The country has also invested heavily in digital health technologies, including telemedicine and remote consultations and monitoring, which improve access to care, particularly in rural areas, given the geographic characteristics of the country.

Central to the reform was strengthening general practice/family medicine as the backbone of PHC. Special attention has been given to training family doctors in the new system of interaction with patients, which places a greater focus on patients' needs. Family doctors who are members of multidisciplinary teams have upgraded their skills by improving their clinical knowledge in evidence-based medicine and non-clinical competencies in areas such as communication with patients and within the PHC team and assessing the individual medical and social needs of patients[9, 10].

The government has made notable progress in integrating mental health services into PHC, with medical psychologists and social workers now part of PHC teams. This integration aims to comprehensively address the population's psychological needs. Insights from innovative PHC practices highlighted the importance of strengthening primary care teams by granting them greater professional autonomy and enhancing the skills of nurses, social workers, and psychologists to provide better PHC responses to meet people's needs comprehensively, but there are still some improvements necessary to determine the responsibilities and functions of these mental health care specialists[11].

Outpatient drug supply at the PHC level has increased in recent years: free ambulatory drugs provision has been expanded from 48 in 2019 to 126 diseases in 2023 covering about 4 million people. Access to expensive diagnostics like CT and MRI has increased in recent years, too.

The Republic of Kazakhstan has made a substantial breakthrough in healthcare informatization, guided by a long-term strategic vision aimed at creating an integrated information environment. This environment ensures access to essential data for all key stakeholders, including the population, healthcare providers, medical professionals, as well as management and financing bodies. Key elements of the system consist of an electronic health record (EHR) repository, a data analytics platform equipped with business intelligence tools, and a patient access portal. Achieving this vision requires full interoperability across all health information systems and resources, enabling real-time clinical decision-making at every level of care. It reduces barriers between different levels of service delivery and healthcare facilities, while also improving coordination of patient pathways across outpatient and inpatient settings through PHC[12, 13].

Telemedicine has made some significant impact on the improvement of PHC in this country. However, the implementation of telemedicine and its maximum benefits has been a challenge for many medical institutions due to the poor internet coverage and low-capacity digital infrastructure in the country[13].

Current Challenges

The two main challenges facing PHC in Kazakhstan now are the growth of non-communicable diseases (NCD) and the challenge of providing UHC[14]. Other areas of concern are infectious diseases, especially HIV/AIDS and tuberculosis and increasing financial burden for PHC.

One of the key challenges facing Kazakhstan's health system is the relatively low level of health expenditure per capita, which stood at US$ 765 in 2019 (purchasing power adjusted). While this figure exceeded the Central Asian regional average of US$ 552, it remained below both the average for upper middle-income countries in the WHO European Region (US$ 1 338) and the overall WHO European Region (US$ 3,226). In the same year, health spending accounted for just 2.8% of GDP, placing Kazakhstan among the lowest in the WHO European Region[15].

Out-of-pocket (OOP) spending on health services represents a critical cause of financial hardship, even in Europe's richest countries. Kazakhstan introduced social health insurance (SHI) to increase health spending and it has had some effect on reducing OOP. Between 2000 and 2021, Kazakhstan's UHC service coverage index rose from 38.7% to 80%. This global indicator, used to monitor progress toward Sustainable Development Goal 3, target 3.8.1, reflects not only a substantial improvement in access to essential health services but also places the country above the WHO European Region average of 77.1%[15].

As ageing is accompanied by a rising prevalence of chronic and disabling conditions, evidence increasingly highlights the importance of PHC in delivering continuous, comprehensive, and well-coordinated services. PHC also plays a key role in addressing social inequalities in health. In contrast, hospitals are less suited for preventive services or the long-term management of chronic illnesses. From both a clinical and economic perspective, strengthening PHC systems is therefore a logical priority for healthcare systems[16].

Ensuring geographical access to PHC care is a challenge in Kazakhstan due to the vast geographic expanse of the country as well as its topography: large deserts, huge territory, and sparsely populated areas exacerbate barriers to healthcare access. The consequences are that the majority of rural settlements in Kazakhstan have low availability of PHC services[16].

Over the first decade following independence (1990s into the early 2000s), the burden of disease changed considerably and the inherited model of care struggled to address it. The growth of non-communicable diseases (NCD) and the challenge of providing UHC placed an increased financial burden on the PHC system. Cardiovascular diseases and cancer became the leading causes of mortality[17], although as mentioned earlier, infectious diseases especially HIV/AIDS and tuberculosis remained of relative concern.

Kazakhstan ranks among the countries with the highest levels of premature mortality from NCDs in the WHO European Region. NCDs account for 84% of all deaths in the country, with cardiovascular diseases (CVDs) responsible for more than half (54%) of these cases.

Although there is an overall downward trend in premature mortality due to the major NCDs, cardiovascular diseases remain the primary cause of premature mortality. The global burden of disease (GBD) estimates that elevated blood pressure, poor dietary habits, tobacco use, excess body weight, harmful alcohol consumption, and raised fasting plasma glucose are the main contributors to combined morbidities in Kazakhstan. In light of these patterns, the demand is growing for both accessible and high-quality services for the early identification and management of high-risk individuals for CVDs[17, 18].

The capacity of PHC to detect and control these problems shows mixed results, promising but uneven. For example, screening for breast cancer (BC) detection is part of the national list of benefits, but about 10% of BC patients in Kazakhstan faced treatment delays, which were linked to diagnoses at more advanced stages of the disease. Approximately 69% of the target population was screened in 2015, (75% in the urban areas vs 63% in rural areas), a relatively high proportion relative to OECD countries (58.5%), but in line with EU guidelines suggesting a 75% screening rate of the target population[19].

Delays in BC treatment and late-stage diagnoses were linked to certain women characteristics (advanced age and Russian ethnicity) but there are also regional differences. Kazakhstan's cancer care system is structured by geographic regions, which may lead to differences in how screening programs are implemented across the country[19].

People aged 40 years and older are allowed for free cardiovascular screening in PHC polyclinics. The principles of cardiovascular risk assessment and management, recognized by WHO as one of its 'best buys', have already been incorporated into Kazakhstan's national policies, screening initiatives, and clinical guidelines. However, outcomes still show significant room for improvement[20].

A WHO promoted study exploring ambulatory care sensitive conditions (ACSC) in Kazakhstan raised serious concerns about the quality of PHC. Hospital admissions for ACSCs in Kazakhstan are high, probably representing weakness in the services delivered at the PHC level, and improving the management of ACSCs outside hospitals remains a priority. Overall, the high rates of hospitalizations for ACSCs were attributed to a range of factors including overburdened PHC providers with limited ability to provide continuity of care, excessive and irrational prescribing of antibiotics, as well as limited adherence to guidelines. PHC organizations still lack comprehensive disease management programs to control conditions like high blood pressure. An estimated 75% of hypertension-related hospital admissions in Kazakhstan could have been prevented with more effective PHC interventions[21].

A significant reflection is the elevated under-detection of conditions such as cardiovascular risk factors, hypertension, and elevated cholesterol level. Underreported diabetes is also very high, with estimates of 50% of cases not being detected[22, 23].

Burnout of PHC professionals in Kazakhstan is high, with significant implications for physicians' personal health. Burnout undermines the quality of care by affecting patient safety, satisfaction, physician turnover, and reduced productivity. While its causes are complex, major contributors include excessive administrative workloads from poorly designed systems, low wages, and weak regulatory frameworks, all of which fuel clinician frustration[24, 25].

Psychiatric care in Kazakhstan remains largely hospital-based, while community and psychosocial services at the PHC level are ineffective. Stigma surrounding mental illness is still prevalent, misconceptions about psychiatry are common, and public awareness of human rights is limited. Recently, however, political attention to mental health has started to increase, accompanied by some encouraging improvements in service provision[24].

Tuberculosis continues to pose a major public health concern, even though its incidence has been gradually declining. Kazakhstan carries one of the heaviest burdens of multidrug-resistant tuberculosis (MDR-TB) globally. Following independence, Kazakhstan retained the centralized Soviet-style tuberculosis control system, which relied heavily on active case detection, individualized treatment, and prolonged hospitalizations, factors that likely contributed to widespread resistance to anti-tuberculosis medications[26,27,28].

To address the escalating TB epidemic, Kazakhstan launched the National Tuberculosis Program and the World Health Organization's Directly Observed Treatment Short-Course strategy in 1998. This shifted care toward an outpatient model, reducing reliance on hospital beds. TB services have since been integrated

into PHC, with daily medication provision and hospital-substitution technologies included[28].

HIV infection is still of concern though not at epidemic levels. The number of newly reported HIV infections in Kazakhstan has risen by 39% since 2010, yet the true extent of the situation remains unclear due to limitations in reliable data and statistics. Moreover, cultural factors, including HIV-related stigma and discrimination, may hinder timely diagnosis and access to treatment[29, 30].

COVID-19 highlighted the structural limitations of the Kazakh healthcare system. It has been estimated that excess mortality in Kazakhstan may be 3.8 times greater than the reported COVID-19 mortality[31, 32].

Discussion

The health system in Kazakhstan has made significant positive developments following the Alma Ata Declaration in 1978 and in the post-independence era after 1990. Further commitment to the principles of the PHC was adopted at the Astana Declaration on Primary Health Care (PHC) in October 2018 at the Global Conference on Primary Health Care in Astana, the current capital of the Republic of Kazakhstan. The conference emphasized the foundational principles of the 1978 Alma-Ata Declaration, and reaffirmed global commitment to strengthening PHC as a central element to achieving UHC in line with the Sustainable Development Goals (SDGs), providing a strategic framework for countries to develop and strengthen their PHC systems, ultimately aiming to achieve better health outcomes and greater health equity[1].

The implementation of the PHC and the achievement of its health-level outcomes still face major challenges in Kazakhstan due to the low level of funding, urban-rural differences, low quality trained personnel, and financing to expand a secondary care-intensive and specialist-led approach to NCDs.

The Social Health Insurance Fund, established in 2016, now plays a crucial role in financing healthcare, covering a broad range of services and reducing the financial burden on citizens.

Kazakhstan's PHC has seen substantial improvements through policy reforms, increased funding, and the adoption of innovative technologies. The current reallocation of funding is enhancing the efficiency of health expenditures, supported by incentives that encourage a shift from inpatient care toward day and ambulatory services. Additional opportunities remain to improve payment mechanisms for providers, including the introduction of case-based financing for hospital services, which have now been introduced for rural hospitals, supplemented with additional coefficients.

It will expand knowledge of effective practices, encourage the design and implementation of reform agendas, and promote the adoption of innovative technologies, with the aim of strengthening NCD management at the PHC level in underserved regions to reduce inequalities, strengthening governance and institutional capacity to achieve UHC and SDG.

Greater investment in preventive measures is essential to save lives, while strengthening NCD management models, covering early detection, curative, therapeutic, and palliative care, can further reduce morbidity and mortality, boost productivity, and lower the risk of impoverishment among vulnerable groups, particularly women and populations in underserved areas.

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References

1. Kluge H, Kelley E, Birtanov Y, et al. Implementing the renewed vision for Primary Health Care in the Declaration of Astana: the time is now. Prim Health Care Res Dev. 2019;20:e137. doi:10.1017/S1463423619000719.

2. Glushkova N, Semenova Y, Sarria-Santamera A. Editorial: Public health challenges in post-Soviet countries during and beyond COVID-19. Front Public Health. 2023;11:1290910. doi:10.3389/fpubh.2023.1290910.
3. Katsaga A, Kulzhanov M, Karanikolos M, Rechel B. Kazakhstan: Health System Review. Health Syst Transit. 2012;14(4):1-154.
4. Bureau of National statistics, Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. [Internet]. Available from: https://stat.gov.kz/ru/industries/economy/national-accounts/publications/117664/
5. State Health Care Reform and Development Program of the Republic of Kazakhstan for 2005-2010. [Internet]. Available from: https://do.gendocs.ru/docs/index
6. Order of the Government of the Republic of Kazakhstan. [Internet]. Available from: https://cis-legislation.com/document.fwx?rgn=110591
7. Order of the Government of the Republic of Kazakhstan on compulsory social medical insurance. Law of the Republic of Kazakhstan, November 15, 2015; 405 (V). [Internet]. Available from: https://adilet.zan.kz/eng/docs/Z1500000405
8. Order of the Government of the Republic of Kazakhstan of December 26, 2019; 289. [Internet]. Available from: https://cis-legislation.com/document.fwx?rgn=121946
9. European Observatory on Health Systems and Policies. Health Systems in Action. Kazakhstan. Heath Systems in Action insight series September 12, 2022. [Internet]. Available from: https://eurohealthobservatory.who.int/publications/i/health-systems-in-action-kazakhstan-2022
10. Orynbassarova D. Family Medicine as a Model of Primary Health Services Delivery: A Pilot Study in Almaty, Kazakhstan. Cent Asian J Glob Health. 2015;4(1):209. doi:10.5195/cajgh.2015.209.
11. Ryapolova N, Galea JT, Greene KY. Perceptions towards integrated care through the narrative of practicing social workers and psychologists in PHC: a cross-case analysis. Journal of Integrated Care. 2023;31(1):75-85. doi:10.1108/JICA-08-2022-0042.
12. Abishev O, Spatayev Y. The future development of digital health in Kazakhstan. Eurohealth. [Internet]. Available from: https://iris.who.int/bitstream/handle/10665/332524/Eurohealth-25-2-24-26-eng.pdf
13. Makasheva RS, Tussupova LA, Giese R. The process of telemedicine implementation in the context of the digitalization process in Kazakhstan. Economics: The Strategy and Practice. 2022;17(3):49-65. doi:10.51176/1997-9967-2022-3-49-65.
14. Davletov K, Nurgozhin T, McKee M. Reflecting on Alma Ata 1978: forty years on. Eur J Public Health. 2018;28(4):587. doi:10.1093/eurpub/cky094.
15. OECD Reviews of Health Systems: Kazakhstan 2018. Paris: OECD Publishing; 2018. doi:10.1787/9789264289062-en.
16. Shaltynov A, Rocha J, Jamedinova U, Myssayev A. Assessment of primary healthcare accessibility and inequality in north-eastern Kazakhstan. Geospat Health. 2022;17(1). doi:10.4081/gh.2022.1046.
17. Mukasheva G, Abenova M, Shaltynov A. Incidence and Mortality of Cardiovascular Disease in the Republic of Kazakhstan: 2004-2017. Iran J Public Health. 2022;51(4):821-30. doi:10.18502/ijph.v51i4.9243.
18. Institute for Health Metrics and Evaluation (IHME). Kazakhstan. Forecasted data based on Global Burden of Disease 2017. [Internet]. Seattle, WA: IHME; Available from: https://www.healthdata.org/research-analysis/health-by-location/profiles/kazakhstan
19. European Commission. European guidelines on breast cancer screening and diagnosis. [Internet]. Available from: https://cancer-

screening-and-care.jrc.ec.europa.eu/en/ecibc/european-breast-cancer-guidelines

20. Glushkova N, Turdaliyeva B, Kulzhanov M. Examining disparities in cardiovascular disease prevention strategies and incidence rates between urban and rural populations: insights from Kazakhstan. Sci Rep. 2023;13:20917. doi:10.1038/s41598-023-47899-8.
21. Supiyev A, Nurgozhin T, Zhumadilov Z, Peasey A, Hubacek JA, Bobak M. Prevalence, awareness, treatment and control of dyslipidemia in older persons in urban and rural population in the Astana region, Kazakhstan. BMC Public Health. 2017;17(1):651. doi:10.1186/s12889-017-4629-5.
22. Supiyev A, Kossumov A, Utepova L, Nurgozhin T, Zhumadilov Z, Bobak M. Prevalence, awareness, treatment and control of arterial hypertension in Astana, Kazakhstan. A cross-sectional study. Public Health. 2015;129(7):948-53. doi:10.1016/j.puhe.2015.02.020.
23. Orazumbekova B, Issanov A, Atageldiyeva K. Prevalence of Impaired Fasting Glucose and Type 2 Diabetes in Kazakhstan: Findings From Large Study. Front Public Health. 2022;10:810153. doi:10.3389/fpubh.2022.810153.
24. Uristemova A, Myssayev A, Meirmanov S, Migina L, Pak L, Baibussinova A. Prevalence and associated factors of depression, anxiety, and stress among academic medicine faculty in Kazakhstan: a Cross-sectional Study. J Prev Med Hyg. 2023;64(2):E215-E225. doi:10.15167/2421-4248/jpmh2023.64.2.2932.
25. DiGiorgio AM, Ehrenfeld JM, Miller BJ. Improving Health Care Quality Measurement to Combat Clinician Burnout. JAMA. 2023;330(12):1135–1136. doi:10.1001/jama.2023.15512.
26. World Health Organization. Tuberculosis Epidemiological impact analysis and assessment of TB surveillance system of Kazakhstan. 2019. [Internet]. Available from: https://www.euro.who.int/__data/assets/pdf_file/0012/399882/kazakh-epireview-finaledited.pdf
27. Maimakov T, Sadykova L, Kalmataeva Z. Treatment of tuberculosis in South Kazakhstan: clinical and economical aspects. Medicina (Kaunas). 2013;49(7):335–40.
28. Darisheva M, Tracy M, Terlikbayeva A, Zhussupov B, Schluger N, McCrimmon T. Knowledge and attitudes towards ambulatory treatment of tuberculosis in Kazakhstan. BMC Health Serv Res. 2020;20(1):563. doi:10.1186/s12913-020-05413-0.
29. Bilibayeva G, Ospanova D, Nurkerimova A, et al. Epidemiological Analysis of HIV/AIDS in Kazakhstan during 2018-2020. J Res Health Sci. 2023;23(2):e00580. doi:10.34172/jrhs.2023.115.
30. Iskakova B, Nugmanova Z, Murat Yucel R, Gamarel KE, King EJ. Re-validation and cultural adaptation of the brief, standardized assessment tool for measuring HIV-related stigma in healthcare settings in Almaty, Kazakhstan. PLoS One. 2022;17(11):e0276770. doi:10.1371/journal.pone.0276770.
31. Sarria-Santamera A, Abdukadyrov N, Glushkova N. Towards an Accurate Estimation of COVID-19 Cases in Kazakhstan: Back-Casting and Capture-Recapture Approaches. Medicina (Kaunas). 2022;58(2):253. doi:10.3390/medicina58020253.
32. Sachs JD, Horton R, Bagenal J, Ben Amor Y, Karadag Caman O, Lafortune G. The lancet COVID-19 commission. Lancet. 2020;396(10249):454. doi:10.1016/S0140-6736(20)31494-X.

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Review Article

Behavioral Impacts of AI Reliance in Diagnostics: Balancing Automation with Skill Retention

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Abstract:
The rapid application of artificial intelligence (AI) in diagnostic disciplines such as radiology, pathology, microbiology, and genomics has revolutionized the way in which doctors and laboratory workers provide patient care. AI has enhanced the efficacy, accuracy, and cost-effectiveness of laboratory operations, clinical decision support systems, and image interpretation. However, these advantages are accompanied by a severe behavioral issue: an excessive reliance on automation could result in a generation of professionals who lack the reasoning abilities necessary to independently assess or contextualize machine outputs. The dual effects of AI integration are the focus of this paper, which highlights its beneficial aspects—including decreased cognitive load, increased confidence, and educational reinforcement—as well as its adverse effects, which include skill degradation, diagnostic deskilling among trainees, complacency, and reduced situational awareness. The research emphasizes the potential for unregulated dependence on AI to progressively alter professional conduct and expertise by utilizing case examples from radiology, pathology, laboratory medicine, and clinical decision support, as well as parallels from automation in aviation. In order to address these concerns, a conceptual framework is proposed that integrates AI into a "human-in-the-loop" approach, thereby preserving the significance of human judgment while leveraging machine accuracy. In order to achieve equilibrium, strategies include curriculum reform to integrate AI with hands-on experience, regular retraining, the implementation of explainable AI to promote active thinking, and institutional measures similar to recurrent training in high-stakes sectors. Ultimately, AI should complement the existing infrastructure rather than supplant it. In order to guarantee this, we must establish strategic educational, organizational, and regulatory safeguards to preserve diagnostic expertise, ensure accountability, and maintain the resilience of healthcare systems as they become increasingly dependent on intelligent technologies.

Keywords: Artificial Intelligence (AI) in Diagnostics; Human-in-the-Loop; Skill Retention; Clinical Decision Support; Diagnostic Automation

Introduction

The use of AI in modern medicine for diagnosis is on the rise. The production and application of diagnostic information by healthcare professionals are being rapidly transformed by AI. This includes the automation of microbiological culture and clinical decision support systems, as well as the interpretation of radiological images and the analysis of digital pathology slides. These computers are capable of assessing vast datasets, identifying nuanced patterns that may be overlooked by humans, and providing findings in a timely and consistent manner. AI has enhanced the efficacy of clinical workflows, reduced turnaround times, and improved diagnostic yield in oncology imaging, automated hematology, and infectious disease diagnostics (1).

AI has the potential to improve the accuracy and efficacy of predictions and reduce human error. The diagnostic precision of human specialists can be matched or surpassed by machine learning algorithms that have been trained on extensive annotated datasets. In resource-constrained healthcare settings, where diagnostician shortages can negatively impact patient outcomes, this ability to facilitate more rapid and precise clinical decision-making is essential. By outsourcing repetitive operations, AI can also enable physicians and laboratory workers to concentrate on complex situations, patient communication, and multidisciplinary collaboration (2,3).

A behavioral issue arises, despite these advances. The increasing use of AI may result in the loss of diagnostic reasoning and practical skills among clinicians and laboratory experts. Professionals may be inclined to embrace AI-derived conclusions without exercising critical thinking due to automation bias, which involves placing faith in algorithmic outputs. This may result in the gradual deterioration of manual diagnostic skills, interpretive judgment, and pattern identification. In professions where tacit competence, which is acquired through years of experiential learning, is essential, skill attrition impacts health systems and practitioners (4,5).

Technical performance metrics—specificity, accuracy, sensitivity, and predictive validity—have been the primary focus of AI diagnostics research. Although significant, these assessments neglect to account for the cognitive and behavioral consequences of ongoing AI utilization. It is uncertain how AI-augmented environments maintain diagnostic knowledge, modify training paradigms, and transform the professional identities of clinicians. Healthcare may compromise long-term competence in favor of short-term efficiency if these characteristics are not carefully considered (6).

This research critically evaluates the behavioral implications of AI-based diagnostics, with a particular emphasis on the tension between automation and skill retention. In order to demonstrate the advantages and obstacles of AI integration, we integrate cognitive psychology, diagnostic medicine, and automation-intensive industry learning. Lastly, the report recommends strategies for the creation of AI-powered systems and training programs that safeguard the diagnostic abilities of healthcare professionals.

Methodology: Narrative Synthesis

In this study, a narrative synthesis approach was employed to assess the impact of artificial intelligence (AI) in diagnostics. A comprehensive literature search was conducted using databases such as PubMed, Google Scholar, and IEEE Xplore, focusing on studies published between 2015 and 2023 that evaluated AI applications in diagnostic imaging, pathology, and clinical decision support systems. Studies were selected based on inclusion criteria that prioritized peer-reviewed, quantitative research examining AI's impact on diagnostic accuracy and error reduction. Key data were extracted from the selected studies, including success rates, accuracy statistics, and the types of AI systems used. These findings were then synthesized into thematic categories, such as radiology, pathology, and clinical decision support, to highlight the benefits and challenges of AI integration. The synthesis also integrated case studies, providing practical examples of AI's effects on diagnostic practice. Each study was critically appraised for methodological quality, and limitations such as sample size and potential biases were acknowledged. In cases where statistical data were available, basic analyses were performed to summarize the overall effectiveness of AI. The results were presented in a coherent narrative format, incorporating both quantitative data in summary tables and qualitative insights into the behavioral impacts of AI in diagnostic workflows. This methodology allowed for a comprehensive

understanding of AI's role in diagnostics while ensuring that the synthesis of findings was both rigorous and actionable.

Conceptual Framework: AI Reliance and Human Cognition

In order to comprehend the behavioral consequences of AI in diagnostics, cognitive and psychological models of human interaction with automation are required. The psychology of automation has long acknowledged that technology systems in professional practice alter processes and their users' cognitive strategies. This dynamic is characterized by complacency, automation bias, and technology faith. In order to adopt algorithmic recommendations, clinicians must have faith in them; however, an excessive amount of faith may result in blind adoption (4,7). Automation bias is a phenomenon in which specialists prioritize AI outputs over divergent clinical data. This could result in complacency, which would render human monitoring perfunctory rather than vigilant, thereby jeopardizing the protections of human-machine collaboration. In this figure, we introduce a conceptual framework that demonstrates the impact of the growing dependence on AI in diagnostic practice on human cognition and behavior. The diagram emphasizes the interaction between cognitive effects, including automation bias, complacency, and cognitive outsourcing, and their subsequent behavioral consequences, which include disengagement, reduced situational awareness, and skill erosion (8). This framework functions as a visual aid to assist readers in understanding the dual consequences of AI dependence on professional practice, which can both enhance and potentially undermine diagnostic expertise.

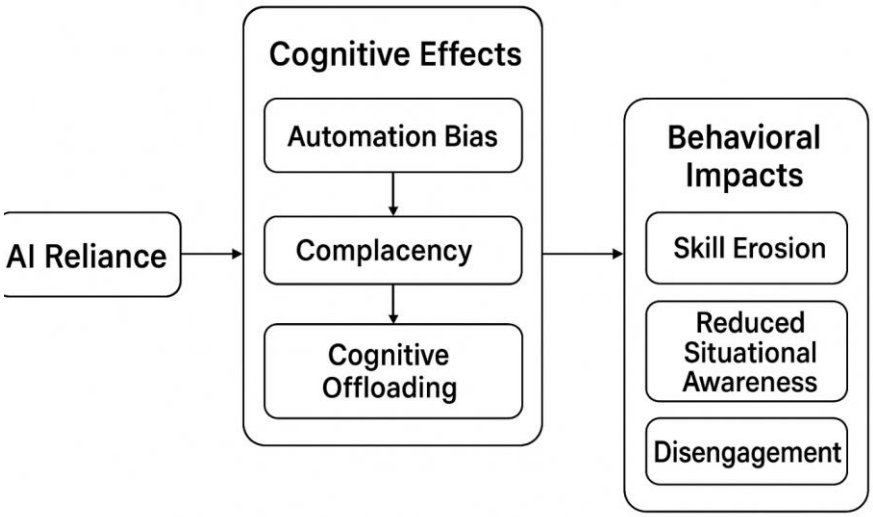

Figure 1. Conceptual Framework of AI Reliance and Human Cognition

Figure 1 illustrates the conceptual framework of AI dependence and human cognition. The cognitive and behavioral repercussions of AI reliance are illustrated in this flowchart. It demonstrates the cognitive effects that can result from a reliance on AI, such as increased automation bias and complacency. These effects will subsequently influence professional behavior, resulting in outcomes such as skill erosion and disengagement. The delicate equilibrium between the advantages and obstacles presented by AI in diagnostic environments is illustrated in this figure.

Cognitive offloading, which involves the transfer of intricate cognitive tasks to external instruments, is interconnected. Offloading enhances efficacy in diagnostic medicine; however, it incurs concealed expenses. Clinicians who frequently employ artificial intelligence (AI) to assess radiological abnormalities or propose differential diagnoses may impair their cognitive abilities and neural pathways, which are essential for independent diagnostic judgment. Cognitive outsourcing has the potential to transform AI into a decision-making substitute, which could have an impact on professional autonomy and critical thinking (4).

The manual flying skills of pilots are impaired by the protracted use of autopilot technology in aviation. Strong diagnostic medicine similarities exist. If automation fails, clinicians must maintain their proficiency by practicing interpretative and manual diagnostic skills, regardless of the presence of AI. The paradox of auto-

mation is exemplified by skill decay: clinicians may become more vulnerable when human intervention is required, as AI becomes more reliable, and they may rely less on their knowledge (9).

Diagnostic competence is contingent upon tacit information that is not susceptible to modeling. Clinical intuition, experiential judgment, and aberrant pattern recognition are developed through years of experience and guidance. These abilities are challenging to impart to machines as a result of contextual interpretation, patient history integration, and holistic reasoning. Preserving this expertise is essential for the preservation of the quality of treatment and the provision of the necessary knowledge for independent practice to future clinicians (10).

These issues can be resolved through a "human-in-the-loop" approach. This approach underscores complementarity: AI offers rapid, data-driven insights, while physicians employ contextual judgment, ethical reasoning, and experiential competence. This approach preserves human agency, mitigates skill erosion, and establishes a symbiotic relationship in which automation improves human cognition. This paradigm enables researchers to investigate the behavioral consequences of AI's reliance and devise solutions that strike a balance between automation and skill retention (11).

Positive Behavioral Impacts of AI Reliance

It is imperative to acknowledge the beneficial effects of AI on behavior when it is implemented in clinical settings, despite the legitimate concerns regarding the excessive reliance on AI in diagnostics. Upon cautious application, these advantages demonstrate that AI has the potential to enhance human performance, rather than detract from it. This has the potential to alter how professionals conduct themselves in a positive manner (12).

One benefit is that AI support instills greater confidence in physicians. Diagnostic medicine is characterized by a significant amount of ambiguity, particularly in cases where the circumstances are uncertain or precarious. By verifying their assessments, AI can assist physicians in developing a greater sense of assurance in their decisions. This psychological reinforcement has the potential to improve the speed of decision-making, reduce the fear of costly errors, and reduce the likelihood of hesitation when making a diagnosis. AI is not merely a technical instrument; it is also a confidant who enhances your self-assurance (12,13).

It is also crucial to reduce the cognitive workload. In some cases, diagnostic activities require the simultaneous analysis of complex data, such as clinical history, laboratory findings, and imaging investigations, within a limited timeframe. By outsourcing routine or repetitive components of the process, AI enables physicians to redirect their mental resources from lower-level responsibilities to higher-level reasoning and patient-centered tasks. Experts may allocate additional time to nuanced clinical interpretation, collaboration with individuals from diverse disciplines, and patient engagement in meaningful ways, as opposed to managing the entire data processing process (14).

AI can also be employed for educational purposes, such as serving as an interactive instructor in training environments. Medical students, residents, and lab trainees receive immediate feedback on their diagnostic reasoning through AI-generated annotations or suggestions. By highlighting errors, reinforcing appropriate techniques, and providing learners with a diverse array of diagnostic scenarios, this iterative learning environment facilitates their development into experts. AI-assisted learning has the potential to expedite the acquisition of new skills and ensure that instruction remains consistent across various types of institutions over time (15).

The most intriguing development is the emergence of collaborative intelligence, which integrates the most advantageous aspects of human judgment and computer analysis. Artificial intelligence (AI) possesses computational power, consistency, and the capacity to identify patterns on a large scale, while humans contribute contextual awareness, moral reasoning, and the capacity to manage uncertainty. This connection supports the notion that "the whole is greater than the sum of its parts." AI has the potential to assist physicians in the development of more accurate diagnoses, rather than supplanting them (16). This establishes a method of operation that integrates algorithmic precision and human cognition. AI has undeniably brought several advantages to the diagnostic process, including enhanced efficiency, reduced cognitive load, and greater confidence in clinical decision-making. However, while AI offers notable benefits, it also presents significant challenges that cannot be overlooked. The increasing reli-

ance on AI has raised concerns regarding skill degradation, deskilling, and complacency among healthcare professionals.

Negative Behavioral Impacts of AI Reliance

Even if artificial intelligence (AI) has the potential to change the way we do things, using it in diagnostics raises a lot of behavioral issues. The long-term integrity of clinical knowledge is at jeopardy because of too much dependence on automation, the loss of important skills, and less professional participation. If we want to get the most out of AI without putting the skills that make treatment possible at risk, we need to think carefully about these problems (3).

Over-reliance and Complacency

One of the most immediate behavioral risks is that therapists tend to trust AI systems too much. Automation bias, which is the tendency to believe what machines say without checking it, leads to complacency. When AI is always right in everyday tasks, experts may soon stop actively checking diagnostic data and just start receiving it. This pattern is similar to what has been seen in aviation, where too much dependence on autopilot has been connected to a number of serious accidents. In medicine, this kind of complacency could lead to a culture of algorithm deference, where doctors might miss mistakes or uncommon cases that the AI's training data doesn't cover (4).

Skill Erosion

Diagnostic medicine has always relied on repeated practice and hands-on learning to build expertise. Pathologists, for example, refine their skills by analyzing countless slides under a microscope, whereas radiologists learn pattern recognition after years of image interpretation. As AI performs more of these tasks, opportunities for hands-on experience diminish, resulting in a continuous decline in technical and interpretative skills. This erosion is especially concerning in laboratory medicine, where less involvement with manual microscopy or culture interpretation may risk the ability to troubleshoot when automated methods fail. Once entrenched, skill loss is difficult to reverse, and it may result in a generation of doctors who are ill-equipped to operate without technological assistance (17).

Diagnostic Deskilling in Training

The risks of skill erosion are higher in educational contexts. Trainees who encounter AI early in their careers may avoid the difficult task of developing autonomous diagnostic thinking. Students who are continually exposed to AI-generated responses may conclude that critical thinking is unnecessary, making it difficult for them to develop professional judgment. The complex, instinctual abilities evolved while managing diagnostic uncertainty—such as pattern recognition, probabilistic reasoning, and extensive data synthesis—are less likely to arise in environments where AI provides quick, conclusive conclusions. This makes me concerned about the future workforce, which is better at verifying computer ideas than making diagnoses on its own (18).

Loss of Situational Awareness

Another behavioral consequence is the potential loss of situational awareness. In diagnostic practice, situational awareness refers to the clinician's overall comprehension of the patient's condition, which includes clinical history, contextual markers, and environmental effects. Overemphasis on AI outputs may limit clinicians' concentration, leading to a fragmented understanding of the diagnostic process. For example, a doctor who utilizes AI to analyze radiological scans may fail to connect the data with minor clinical details, and a lab scientist who uses automated culture methods may overlook distinct development patterns that are critical for therapeutic purposes. This type of limited perspective may result in less full and precise care (19).

Bias Reinforcement

AI systems are only as powerful as the data they learn from. When models inherit biases, such as not covering specific categories of people or focusing too heavily on prevalent diseases, these biases can be perpetuated or even exacerbated. A behavioral risk develops when clinicians are accustomed to deferring to AI and fail to question outputs that contradict clinical intuition or patient-specific concerns. Human professionals do not correct systemic prejudice; rather, they act as a passive channel for it, exacerbating discrepancies in diagnostic results. The psychological tendency to avoid analyzing "authoritative" computer outputs exacerbates this risk, raising significant ethical and equity concerns (20).

Psychological Disengagement

The most dangerous consequence of relying on AI is the risk of losing interest in the diagnostic process itself. As professionals transition from active diagnosticians to passive overseers of machine operations, their roles may shift from data interpreters to technicians who check predetermined outputs. This alteration not only makes diagnostic work less intellectually exciting, but it also undermines professional identity. If not addressed, this lack of engagement may result in poorer work satisfaction, a desire to continue learning, and a diminished sense of responsibility for patient outcomes. Finally, healthcare staff may feel disconnected from the talents that once defined their roles (12).

Synthesis

These negative consequences on behavior demonstrate a paradox inherent in AI integration. Automation has the potential to enhance speed and precision; yet, over-reliance on technology may undermine essential human competencies—critical reasoning, pattern recognition, and contextual judgment—that are fundamental to robust diagnoses. The deterioration of these capacities is not an inevitable outcome but a behavioral trajectory shaped by the design, implementation, and integration of AI systems into workflows. If clinicians don't take steps to safeguard themselves on purpose, they could become excessively reliant, complacent, and disengaged, which could put both patients and healthcare systems at risk. We need to work on our technical abilities and make plans for how to protect and strengthen the cognitive and professional parts of diagnostic practice to deal with these threats (21,22).

The table below shows the good and bad effects that relying on AI in diagnostics can have on behavior. We list the good effects on the left, such as more confidence, less cognitive load, better learning, and more collaborative intelligence. We list the possible concerns on the right, such as over-reliance, skill degradation, diagnostic deskilling, bias reinforcement, and disengagement. This comparison chart shows that AI has both good and bad effects, giving us a balanced view of the pros and cons of using automation in healthcare (23).

Table 1: Positive vs. Negative Behavioral Impacts of AI in Diagnostics

This table summarizes the positive and negative behavioral impacts of AI in diagnostics, highlighting key areas where AI enhances clinical practice and areas of concern.

Positive Impacts	Negative Impacts
Confidence Boost	Over-reliance on AI
Reduced Cognitive Load	Skill Erosion
Educational Reinforcement	Diagnostic Deskilling
Collaborative Intelligence	Bias Reinforcement
Enhanced Decision Making	Disengagement

Case Study Evidence

The behavioral effects of AI dependency are not merely theoretical; they are already visible in a number of diagnostic medicine domains. Evidence from case studies shows how automation can increase productivity while also raising issues with skill deterioration and complacency. These instances from the fields of radiology, pathology, microbiology, and clinical decision support demonstrate how the use of AI may alter professional workflows in ways that should be carefully evaluated (3).

Radiology

One of the earliest and most evident applications of AI, particularly for image interpretation, was in radiology. Now, issues like brain hemorrhages, bone fractures, and lung nodules can be promptly detected by algorithms that have been trained on vast volumes of imaging data. Throughput has been improved by these techniques, particularly in busy areas like emergency rooms. However, some are concerned about their impact on training. AI-generated annotations may now be used by junior radiologists, who typically acquire experience by closely examining a large number of images. This can expedite the interpretation process, but it may also shorten the experiential learning required to build self-sufficient diagnostic abilities (24).

AI algorithms have significantly improved efficiency in interpreting radiological images, leading to faster diagnosis. Research shows that AI systems can achieve up to 95% accuracy in detecting conditions such as lung cancer, dramatically reducing diagnostic errors.

This technological advancement is transforming the field by providing more reliable and quicker results, though it may come at the cost of hands-on experience for trainees (25). However, this has also raised concerns about reduced hands-on experience for trainees. With AI-generated annotations becoming more common, there is a risk that junior radiologists may rely too heavily on these tools instead of developing independent interpretive skills, which are crucial for accurate diagnosis in complex cases (26).

Pathology and Laboratory Medicine

Digital pathology has been demonstrated to be more efficient and consistent when AI algorithms are able to monitor biomarkers and recognize histological patterns. But relying on these technologies has reduced the number of pathologists who examine glass slides under a microscope. In situations where artificial intelligence serves as the primary interpretive tool, the hand dexterity, visual acuity, and interpretive skills acquired by repeated microscopy may decrease. This worries me about the pathologists of the future, who may lack the manual skills necessary to function well in environments without sophisticated computer infrastructure (27).

In digital pathology, AI has made processes more efficient, enabling pathologists to quickly monitor biomarkers and recognize patterns in slides. This automation improves diagnostic speed and consistency. However, this reliance on AI for primary interpretation can diminish essential manual diagnostic skills. Pathologists may lose their ability to analyze glass slides under a microscope, a crucial skill for future generations, especially in environments without sophisticated computer infrastructure (28).

AI-powered digital pathology tools have been shown to reduce errors by 25% when monitoring biomarkers and histological patterns (29). This increased accuracy enhances diagnostic speed, but over-reliance on AI tools may lead to diminished manual diagnostic skills among pathologists, such as analyzing glass slides under a microscope. To illustrate the effectiveness of AI in diagnostic imaging, the following table summarizes key success rates and impacts across various applications, including radiology, pathology, and clinical decision support.

Table 2: AI Success Rates in Diagnostic Imaging
This table summarizes the success rates and impact of AI applications in various diagnostic imaging fields, highlighting key statistics related to accuracy and error reduction.

AI Application	Success Rate/Impact	Source
Radiology (Lung Cancer Detection)	95% accuracy in detecting lung cancer	Google Health, 2021(30)
Radiology (Breast Cancer Detection)	94.6% accuracy in detecting breast cancer	Stanford University, 2020(31)
Pathology (Biomarker Monitoring)	25% reduction in diagnostic errors in cancer diagnosis	Computational Pathology Research, 2019(32)
Clinical Decision Support (Drug-Drug Interaction)	30% reduction in diagnostic errors	Clinical Decision Support Systems Study, 2018(33)

Microbiology

Automation has also significantly altered microbiology laboratories. Samples can be processed in a timely and consistent manner by systems that can autonomously incubate cultures, take pictures, and identify organisms. However, microbiologists are unable to cultivate their delicate interpretative abilities, such as the ability to identify toxins, mixed growth patterns, or unusual morphologies, due to the fact that they are no longer required to examine cultures as closely as they once were. Specialists may not be as prepared to identify and resolve issues that do not align with the parameters of automated systems when unusual entities emerge (34).

In microbiology, AI-powered automation has significantly sped up the processing and analysis of samples, improving throughput and consistency. While these advancements offer many benefits, they come with a downside. Microbiologists now have fewer opportunities to develop critical interpretive skills, such as the ability to identify rare or unusual pathogens, which

can be essential when dealing with complex cases that do not fit into the automated systems' parameters (35).

Clinical Decision Support

AI-powered technologies provide physicians and pharmacists with drug-drug interaction alerts and recommendations that are based on established guidelines when they are prescribing drugs or making clinical decisions. In numerous scenarios, these methodologies enhance safety; however, they may pose a risk if they are employed excessively, as they may incorrectly identify unusual circumstances. Despite the contradictory patient presentations, case reports demonstrate instances in which physicians relied on decision-support tools, resulting in diagnostic delays or inappropriate therapy. These examples underscore the behavioral risk associated with physicians who prioritize machine authority over contextual judgment (36).

AI-powered decision support systems have helped clinicians identify drug interactions and make diagnostic decisions more efficiently, leading to improved patient safety. However, excessive reliance on these tools can lead to complacency. Clinicians may defer critical thinking and overlook cases that fall outside AI's predefined patterns, potentially leading to diagnostic delays or inappropriate therapy in unusual situations (37). AI-powered decision support systems can reduce diagnostic errors by 30%, providing more consistent and accurate diagnostic readings. However, excessive reliance on these systems can lead to complacency, with clinicians potentially overlooking cases that fall outside AI's predefined patterns (38).

These case studies illustrate the real-world implications of AI reliance in diagnostic practice, highlighting both its benefits and its risks. To address these challenges and preserve professional competence, a conceptual framework is proposed that integrates AI into a 'human-in-the-loop' approach.

Lessons from Other Industries

These concerns are exacerbated by comparable aviation issues. When pilots employ autopilot systems frequently, their situational awareness and manual flight abilities deteriorate, rendering them less secure in the event of an automation failure. Medicine is also on a similar trajectory: as physicians become accustomed to allowing AI to perform the diagnostic process for them, they may be unable to provide the same level of assistance in the event of unforeseen or unusual circumstances. The aviation experience demonstrates that organized protections must be implemented to ensure that individuals maintain their alertness and skills. Automation is necessary (28).

These case studies illustrate a consistent trend: AI enhances efficiency, but it also poses a threat to the experiential learning and situational awareness that are essential for competent diagnostic practice. The results indicate that healthcare personnel may replicate the weaknesses identified in other automation-heavy sectors in the absence of intentional initiatives.

Balancing Automation with Skill Retention

The challenge for modern healthcare is not the integration of artificial intelligence (AI) into diagnostics, but rather the implementation of AI in a way that does not compromise the expertise it is intended to improve. In order to achieve this equilibrium, it is imperative that we devise proactive strategies that capitalize on the advantages of automation while also preserving human abilities. In order to ensure that AI complements human diagnostic abilities rather than supplants them, it is necessary to implement a multifaceted approach that encompasses professional culture, regulatory guidance, system design, and education (2).

Education and Training

It is fundamental to modify the curriculum. While maintaining rigorous engagement with manual and interpretative activities, training programs must integrate AI into medical and laboratory instruction. Courses should portray AI as a collaborator that necessitates critical evaluation, rather than as a substitute for human reasoning. For example, radiology residents may be instructed to develop their interpretations before considering AI concepts. This would enable them to enhance their ability to identify patterns and acquire the ability to query algorithmic outcomes. Similarly, pathology and microbiology students could alternate between digital platforms and traditional slide or culture evaluations to ensure that they are proficient in both. The mental and practical foundations of diagnostic expertise are safeguarded by the integration of this dual training philosophy (39).

Human-in-the-Loop Systems

Designing a human-in-the-loop (HITL) system is a practical method of safeguarding oneself at the workflow level. In this approach, AI generates preliminary

findings; however, human experts are required to verify, contextualize, and conclude the diagnosis's interpretation. HITL frameworks ensure that clinicians are accountable and prevent automation from becoming the default authority by mandating human monitoring. This design philosophy not only ensures that specialists remain mentally engaged in the diagnostic process but it also minimizes the likelihood of automation bias. The Human-in-the-Loop (HITL) model, as illustrated in Figure 2, guarantees that AI functions as a supportive instrument. The model emphasizes the interaction between AI analysis, human interpretation, and continuous feedback, thereby ensuring the retention of skills and the accuracy of the analysis (40).

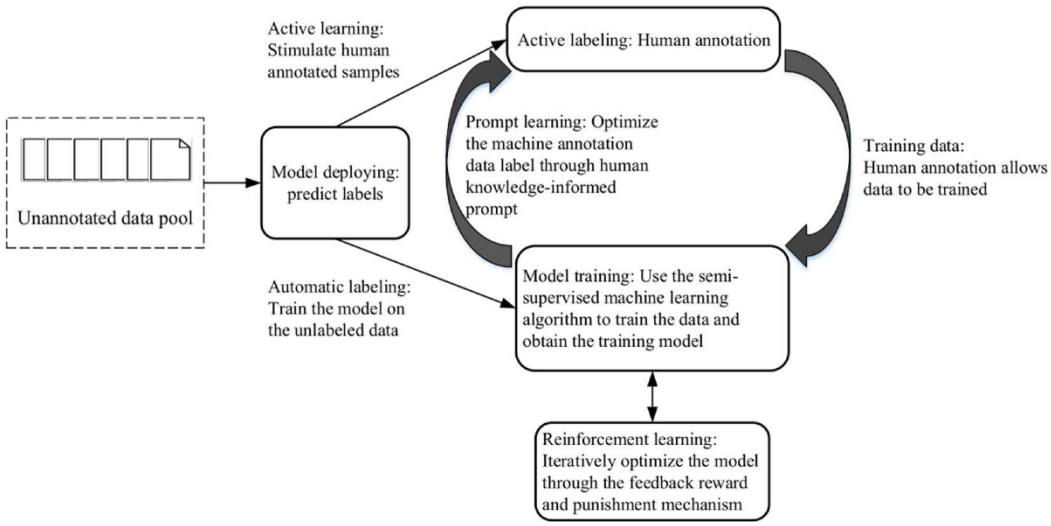

Fig 2: Human-in-the-Loop (HITL) Model for Balancing AI and Expertise in Diagnostics.

This diagram illustrates the Human-in-the-Loop (HITL) model, which integrates human expertise with artificial intelligence (AI) in the diagnostic process. The model consists of multiple stages, starting with an unannotated data pool from which the system selects data for labeling. The process involves active learning to stimulate human annotation and enhance AI's predictive capabilities. Active labeling enables human experts to annotate data, which informs the training of the model through prompt learning and model training. This leads to an optimized AI model that predicts and suggests diagnoses. To ensure continuous improvement, reinforcement learning iteratively refines the AI model using feedback mechanisms, allowing AI and human expertise to complement each other. This approach helps maintain critical diagnostic skills while leveraging the efficiency of AI.

Figure 3. Human-in-the-Loop (HITL) Model for Balancing AI and Expertise

A workflow diagram illustrating the HITL approach in diagnostic medicine: (1) data input (imaging, laboratory findings, clinical records) feeds into (2) AI analysis (pattern recognition and diagnostic suggestions), followed by (3) human expert review (interpretation, contextualization, and final decision-making). A (4) feedback loop ensures both AI refinement and human skill retention. This framework emphasizes AI as a supportive tool rather than a replacement for clinical expertise.

Periodic Retraining and Skill Drills

Structured retraining programs can assist schools and enterprises in combating skill degradation. In the same way that pilots must regularly practice flying by hand, diagnosticians may also engage in skill exercises. For example, laboratories may mandate a specific number of microscopy hours annually, and radiology departments may conduct "blind read" sessions during which physicians evaluate images without the assistance of artificial intelligence. These activities ensure that fundamental skills remain robust, providing a safety net if AI systems malfunction or produce ambiguous results.

Explainable AI (XAI)

Additionally, the design of AI is crucial in assisting individuals in maintaining their abilities. Explainable AI (XAI) systems that display interpretable outcomes, such as highlighting areas of interest on an image or providing reasoning routes for diagnostic ideas, encourage physicians to contemplate the information they observe more thoroughly. It is recommended that professionals query the rationale behind AI judgments

rather than blindly accepting them. This interaction fosters a reflective diagnostic culture, in which AI serves as a catalyst for critical thinking rather than a replacement (41).

Hybrid Decision-Making Protocols

By employing hybrid decision-making principles that establish constraints on AI's autonomy, institutions can enhance the protection of knowledge. AI outputs can be accepted with minimal supervision in everyday, low-risk tasks. Nevertheless, human validation should be necessary in the event of complex, high-stakes, or unusual circumstances. This tier-based methodology guarantees that physicians remain in command when ethical reasoning, context, and judgment are required. Additionally, it prevents individuals from assigning robotics all of their responsibilities in domains where human knowledge is indispensable (9).

Institutional Policy and Regulation

Finally, the integration of skill retention into professional practice necessitates the establishment of institutional rules and regulatory frameworks. Recurrent training and simulation are indispensable in the aviation industry. Healthcare systems may implement a similar policy, mandating that physicians maintain their diagnostic capabilities while employing AI. Professional guidelines may establish standards for the appropriate balance between automated and human-led diagnostics, and accreditation organizations may mandate periodic demonstrations of manual proficiency. Not only do these regulations ensure the safety of patients, but they also safeguard the professional identity of diagnosticians in an era of rapid technological advancement (42).

Synthesis

We do not need to combat AI to achieve a balance between automation and skill retention. Rather, we must establish a diagnostic environment in which the capabilities of both humans and machines are interdependent, thereby enhancing each other's capabilities. By employing education, regulatory monitoring, retraining, explainability, hybrid procedures, and meticulous system design, healthcare can ensure that AI enhances professional knowledge rather than diminishes it. The objective is not to halt automation, but rather to direct it in a responsible manner that preserves the diagnostic resilience that clinicians require both now and in the future (43).

Ethical, Legal, and Professional Implications

The ethical, legal, and professional aspects of medical practice are inextricably linked to the behavioral repercussions of AI's reliance on diagnostics. Automation offers the potential for efficiency and precision; however, it also poses critical concerns regarding accountability, liability, identity, and equity that must be resolved in order to guarantee responsible integration.

Ethical Risk: Diminished Accountability

One of the most critical ethical concerns is the reduction of responsibility that occurs when physicians depend on AI outputs. In the past, diagnostic reasoning placed the entire responsibility on the doctor, who was required to make decisions based on both technical facts and their comprehension of the situation. It is difficult to determine the individual responsible when individuals fail to query the advice of artificial intelligence. Ethical dilemmas arise when errors occur: Who is accountable—the physician, the healthcare institution, or the AI system developers? The ethical foundation of professional accountability in medicine may be compromised if AI is implemented without explicit guidelines (44).

Legal Implications: Malpractice Liability

The law is also subject to the distribution of responsibility. Malpractice liability becomes complex when AI outputs influence diagnostic errors. If the AI commits an error, a physician who adheres to its recommendations may still be held legally accountable. Conversely, disregarding AI recommendations that prove to be accurate may result in litigation. The mixed nature of AI-augmented diagnoses is a challenge for current malpractice frameworks, which are founded on the decision-making processes of individuals. In order to establish a clear understanding of the responsibilities of clinicians, healthcare organizations, and AI developers, the law must be explicit (45).

Professional Identity in Transition

In addition to legal and ethical concerns, the incorporation of AI presents challenges to the professional identity of diagnosticians. The function is at risk of being redefined to prioritize verification and monitoring, despite its traditional reputation for the ability to analyze complex data and make autonomous decisions. The intellectual engagement and perception of expertise that are critical to the diagnostic professions

may be compromised by this type of change. In order to reevaluate professional identity in an AI-augmented environment, clinicians must be viewed as partners rather than as specialists who have been supplanted, as their capacity to evaluate information remains of paramount importance (46).

Equity Considerations

Ultimately, the equity of both training and practice is impacted by the reliance on AI. Institutions that possess sophisticated AI technologies may be capable of providing learners with more automated learning environments. Conversely, individuals with limited resources may continue to depend on manual diagnoses to a significant extent. This discrepancy may result in training pathways that are uneven, as graduates from AI-rich environments may lack the fundamental manual skills required, while those from AI-poor environments may not have had as much exposure to new technology. It is crucial to ensure that training requirements are equitable across various settings in order to prevent the expansion of disparities in professional competence and patient outcomes (18,47).

Future Outlook: AI as Augmentor, Not Replacement

Rather than envisioning the future of diagnostics as one in which AI replaces human expertise, consider it as one in which AI enhances human capabilities. The goal is not to replace the clinician's diagnostic reasoning, but rather to refine and perfect it, ensuring that patients benefit from the combination of human discernment and computer accuracy. This perspective substantiates the significance of professional intuition, contextual reasoning, and tacit knowledge, regardless of the advancements in technology (2,3).

New solutions are already guiding us toward this collaborative future. Adaptive learning platforms can enhance the personalization of training by providing physicians with diagnostic problems that are precisely tailored to their skill level. This promotes active learning in environments that contain a significant amount of AI. Simulation-based retraining exercises can replicate the recurrent training methods used in aviation, ensuring that personnel maintain fundamental competencies despite the increasing automation. Similarly, an environment in which practitioners critically engage with AI rather than passively acquiescing to it could be fostered by ongoing professional development initiatives that integrate AI literacy with fundamental diagnostic competencies (48).

Also, research will be crucial in achieving this future. In order to monitor the influence of AI utilization on diagnostic competencies over time, longitudinal studies on skill retention are essential (49). Additionally, behavioral monitoring may reveal the onset of diminished alertness as a result of automation dependence. In order to facilitate the responsible use of AI, it will be necessary to establish policy frameworks that safeguard human-in-the-loop principles, mandate skill-preservation methods, and establish explicit requirements for AI governance (50).

Ultimately, the message is unmistakable: in an era in which technology is the norm, healthcare systems must safeguard their diagnostic capabilities in order to remain resilient. If medicine views AI as a collaborator rather than a replacement, it may capitalize on its advantages while maintaining the human capabilities that remain the foundation of safe, effective, and compassionate care (51).

Conclusion

AI has the potential to revolutionize diagnostics, improving efficiency, accuracy, and confidence in clinical decision-making. However, its increasing integration also presents significant risks, including skill degradation, complacency, and a reduction in critical thinking. These challenges, if unaddressed, could jeopardize the long-term viability of healthcare systems and the professional competence of clinicians.

While AI can complement and augment human expertise, it should not replace it. The balance between automation and skill retention is crucial to maintaining diagnostic quality and patient safety.

Recommendations:

1. **Regular Retraining Programs**: To safeguard diagnostic expertise, healthcare institutions should implement regular retraining programs that focus on hands-on diagnostic skills, ensuring that clinicians retain their manual and interpretive capabilities even as they integrate AI tools into their practice.

2. **Hybrid Decision-Making Protocols**: We recommend adopting hybrid decision-making frameworks where AI is used as a tool to enhance human decision-making rather than replacing it. These protocols should be designed to incorporate both AI-generated insights and human judgment, especially in complex or high-stakes scenarios.
3. **Curriculum Reform**: Educational institutions should revise their curricula to integrate AI while ensuring that foundational diagnostic skills, such as pattern recognition and manual examination, are retained. AI should be taught as a collaborative tool, encouraging students to verify and question AI outputs rather than defer to them blindly.
4. **Human-in-the-Loop Systems**: The human-in-the-loop (HITL) approach should be prioritized, where AI assists clinicians in their decision-making but human oversight remains central. This ensures that clinicians stay engaged in the diagnostic process, reducing automation bias and fostering continuous skill development.
5. **Regulatory and Ethical Guidelines**: Establish clear regulatory frameworks and ethical guidelines to ensure that AI's implementation in diagnostics is responsible and transparent. These guidelines should focus on maintaining accountability, preventing over-reliance, and ensuring equitable access to AI technologies in healthcare.

By implementing these strategies, healthcare systems can harness the benefits of AI while preserving the critical diagnostic expertise required for safe and effective patient care.

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References

1. Alsulimani A, Akhter N, Jameela F, Ashgar RI, Jawed A, Hassani MA, et al. The Impact of Artificial Intelligence on Microbial Diagnosis. Microorganisms. 2024 May 23;12(6):1051. doi: 10.3390/microorganisms12061051.
2. Krishnan G, Singh S, Pathania M, Gosavi S, Abhishek S, Parchani A, et al. Artificial intelligence in clinical medicine: catalyzing a sustainable global healthcare paradigm. Front Artif Intell. 2023 Aug 29;6:1227091. doi: 10.3389/frai.2023.1227091.
3. Bajwa J, Munir U, Nori A, Williams B. Artificial intelligence in healthcare: transforming the practice of medicine. Future Healthc J. 2021 Jul;8(2):e188–94. doi: 10.7861/fhj.2021-0095.

4. Gerlich M. AI Tools in Society: Impacts on Cognitive Offloading and the Future of Critical Thinking. Societies. 2025 Jan;15(1):6. doi: 10.3390/soc15010006.
5. Junaid SB, Imam AA, Balogun AO, De Silva LC, Surakat YA, Kumar G, et al. Recent Advancements in Emerging Technologies for Healthcare Management Systems: A Survey. Healthcare (Basel). 2022 Oct 3;10(10):1940. doi: 10.3390/healthcare10101940.
6. Al Kuwaiti A, Nazer K, Al-Reedy A, Al-Shehri S, Al-Muhanna A, Subbarayalu AV, et al. A Review of the Role of Artificial Intelligence in Healthcare. J Pers Med. 2023 Jun 5;13(6):951. doi: 10.3390/jpm13060951.
7. Li F, Wang S, Gao Z, Qing M, Pan S, Liu Y, et al. Harnessing artificial intelligence in sepsis care: advances in early detection, personalized treatment, and real-time monitoring. Frontiers in Medicine. 2025 Jan 6;11:1510792. doi: 10.3389/fmed.2024.1510792.
8. Kücking F, Hübner U, Przysucha M, Hannemann N, Kutza JO, Moelleken M, et al. Automation Bias in AI-Decision Support: Results from an Empirical Study. Stud Health Technol Inform. 2024 Aug 30;317:298–304. doi: 10.3233/SHTI240700.
9. Rashid AB, Kausik MAK. AI revolutionizing industries worldwide: A comprehensive overview of its diverse applications. Hybrid Advances. 2024 Dec 1;7:100277. doi: 10.1016/j.hybadv.2024.100277.
10. Pelaccia T, Tardif J, Triby E, Charlin B. An analysis of clinical reasoning through a recent and comprehensive approach: the dual-process theory. Med Educ Online. 2011 Mar 14;16:10.3402/meo.v16i0.5890. doi: 10.3402/meo.v16i0.5890.
11. Karim MM, Khan S, Van DH, Liu X, Wang C, Qu Q. Transforming Data Annotation with AI Agents: A Review of Architectures, Reasoning, Applications, and Impact. Future Internet. 2025 Aug;17(8):353. doi: 10.3390/fi17080353.
12. Chustecki M. Benefits and Risks of AI in Health Care: Narrative Review. Interact J Med Res. 2024 Nov 18;13:e53616. doi: 10.2196/53616.
13. Ahuja AS. The impact of artificial intelligence in medicine on the future role of the physician. PeerJ. 2019 Oct 4;7:e7702. doi: 10.7717/peerj.7702.
14. Jeong J, Kim S, Pan L, Hwang D, Kim D, Choi J, et al. Reducing the workload of medical diagnosis through artificial intelligence: A narrative review. Medicine (Baltimore). 2025 Feb 7;104(6):e41470. doi: 10.1097/MD.0000000000051470.
15. Feigerlova E, Hani H, Hothersall-Davies E. A systematic review of the impact of artificial intelligence on educational outcomes in health professions education. BMC Med Educ. 2025 Jan 27;25:129. doi: 10.1186/s12909-025-06221-w.
16. Liu Y, Fu Z. Hybrid Intelligence: Design for Sustainable Multiverse via Integrative Cognitive Creation Model through Human–Computer Collaboration. Applied Sciences. 2024 Jan;14(11):4662. doi: 10.3390/app14114662.
17. Gaffney H, Mirza KM. Pathology in the artificial intelligence era: Guiding innovation and implementation to preserve human insight. Acad Pathol. 2025 Feb 28;12(1):100166. doi: 10.1016/j.acpath.2024.100166.
18. Vieriu AM, Petrea G. The Impact of Artificial Intelligence (AI) on Students' Academic Development. Education Sciences. 2025 Mar;15(3):343. doi: 10.3390/educsci15030343.
19. Feller S, Feller L, Bhayat A, Feller G, Khammissa RAG, Vally ZI. Situational Awareness in the Context of Clinical Practice. Healthcare (Basel). 2023 Dec 4;11(23):3098. doi: 10.3390/healthcare11233098.

20. Nazer LH, Zatarah R, Waldrip S, Ke JXC, Moukheiber M, Khanna AK, et al. Bias in artificial intelligence algorithms and recommendations for mitigation. PLOS Digit Health. 2023 Jun 22;2(6):e0000278. doi: 10.1371/journal.pdig.0000278.
21. Ahmad SF, Han H, Alam MM, Rehmat MohdK, Irshad M, Arraño-Muñoz M, et al. Impact of artificial intelligence on human loss in decision making, laziness and safety in education. Humanit Soc Sci Commun. 2023;10(1):311. doi: 10.1057/s41599-023-01816-6.
22. Williamson SM, Prybutok V. Balancing Privacy and Progress: A Review of Privacy Challenges, Systemic Oversight, and Patient Perceptions in AI-Driven Healthcare. Applied Sciences. 2024 Jan;14(2):675. doi: 10.3390/app14020675.
23. Kumar Y, Koul A, Singla R, Ijaz MF. Artificial intelligence in disease diagnosis: a systematic literature review, synthesizing framework and future research agenda. J Ambient Intell Humaniz Comput. 2023;14(7):8459–86. doi: 10.1007/s12652-021-03612-z.
24. Obuchowicz R, Lasek J, Wodziński M, Piórkowski A, Strzelecki M, Nurzynska K. Artificial Intelligence-Empowered Radiology—Current Status and Critical Review. Diagnostics (Basel). 2025 Jan 24;15(3):282. doi: 10.3390/diagnostics15030282.
25. Cellina M, Cacioppa LM, Cè M, Chiarpenello V, Costa M, Vincenzo Z, et al. Artificial Intelligence in Lung Cancer Screening: The Future Is Now. Cancers (Basel). 2023 Aug 30;15(17):4344. doi: 10.3390/cancers15174344.
26. Pierre K, Haneberg AG, Kwak S, Peters KR, Hochhegger B, Sananmuang T, et al. Applications of Artificial Intelligence in the Radiology Roundtrip: Process Streamlining, Workflow Optimization, and Beyond. Seminars in Roentgenology. 2023 Apr 1;58(2):158–69. doi: 10.1067/j.ro.2023.03.002.
27. Go H. Digital Pathology and Artificial Intelligence Applications in Pathology. Brain Tumor Res Treat. 2022 Apr;10(2):76–82. doi: 10.14791/btrt.2022.10.e18.
28. Ahuja S, Zaheer S. Advancements in pathology: Digital transformation, precision medicine, and beyond. J Pathol Inform. 2024 Nov 19;16:100408. doi: 10.1016/j.jpi.2024.100408.
29. Baxi V, Edwards R, Montalto M, Saha S. Digital pathology and artificial intelligence in translational medicine and clinical practice. Mod Pathol. 2022;35(1):23–32. doi: 10.1038/s41379-021-00919-2.
30. Ross C. Google's AI improves accuracy of lung cancer diagnosis, study shows [Internet]. STAT. 2019 [cited 2025 Sep 1]. Available from: https://www.statnews.com/2019/05/20/googles-ai-improves-accuracy-of-lung-cancer-diagnosis-study-shows/
31. Thong LT, Chou HS, Chew HSJ, Lau Y. Diagnostic test accuracy of artificial intelligence-based imaging for lung cancer screening: A systematic review and meta-analysis. Lung Cancer. 2023 Feb 1;176:4–13. doi: 10.1016/j.lungcan.2022.11.017.
32. Cui M, Zhang DY. Artificial intelligence and computational pathology. Laboratory Investigation. 2021 Apr 1;101(4):412–22. doi: 10.1038/s41374-020-00514-0.
33. Shahmoradi L, Safdari R, Ahmadi H, Zahmatkeshan M. Clinical decision support systems-based interventions to improve medication outcomes: A systematic literature review on features and effects. Med J Islam Repub Iran. 2021 Feb 22;35:27. doi: 10.47176/mjiri.35.27.
34. Fontana C, Favaro M, Pelliccioni M, Minelli S, Bossa MC, Altieri A, et al. Laboratory

Automation in Microbiology: Impact on Turnaround Time of Microbiological Samples in COVID Time. Diagnostics (Basel). 2023 Jul 1;13(13):2243. doi: 10.3390/diagnostics13132243.

35. Shelke YP, Badge AK, Bankar NJ. Applications of Artificial Intelligence in Microbial Diagnosis. Cureus. 15(11):e49366. doi: 10.7759/cureus.49366.
36. Chalasani SH, Syed J, Ramesh M, Patil V, Pramod Kumar TM. Artificial intelligence in the field of pharmacy practice: A literature review. Explor Res Clin Soc Pharm. 2023 Oct 21;12:100346. doi: 10.1016/j.rcsop.2023.100346.
37. Khosravi M, Zare Z, Mojtabaeian SM, Izadi R. Artificial Intelligence and Decision-Making in Healthcare: A Thematic Analysis of a Systematic Review of Reviews. Health Serv Res Manag Epidemiol. 2024 Mar 5;11:23333928241234863. doi: 10.1177/23333928241234863.
38. Taylor RA, Sangal RB, Smith ME, Haimovich AD, Rodman A, Iscoe MS, et al. Leveraging artificial intelligence to reduce diagnostic errors in emergency medicine: Challenges, opportunities, and future directions. Acad Emerg Med. 2025 Mar;32(3):327–39. doi: 10.1111/acem.15011.
39. Bekbolatova M, Mayer J, Ong CW, Toma M. Transformative Potential of AI in Healthcare: Definitions, Applications, and Navigating the Ethical Landscape and Public Perspectives. Healthcare (Basel). 2024 Jan 5;12(2):125. doi: 10.3390/healthcare12020125.
40. Chen X, Wang X, Qu Y. Constructing Ethical AI Based on the "Human-in-the-Loop" System. Systems. 2023 Nov;11(11):548. doi: 10.3390/systems11110548.
41. Hamida SU, Chowdhury MJM, Chakraborty NR, Biswas K, Sami SK. Exploring the Landscape of Explainable Artificial Intelligence (XAI): A Systematic Review of Techniques and Applications. Big Data and Cognitive Computing. 2024 Nov;8(11):149. doi: 10.3390/bdcc8110149.
42. Slavinska A, Palkova K, Grigoroviča E, Edelmers E, Pētersons A. Narrative Review of Legal Aspects in the Integration of Simulation-Based Education into Medical and Healthcare Curricula. Laws. 2024 Apr;13(2):15. doi: 10.3390/laws13020015.
43. Perifanis NA, Kitsios F. Investigating the Influence of Artificial Intelligence on Business Value in the Digital Era of Strategy: A Literature Review. Information. 2023 Feb;14(2):85. doi: 10.3390/info14020085.
44. Kahraman F, Aktas A, Bayrakceken S, Çakar T, Tarcan HS, Bayram B, et al. Physicians' ethical concerns about artificial intelligence in medicine: a qualitative study: "The final decision should rest with a human." Front Public Health. 2024 Nov 27;12:1428396. doi: 10.3389/fpubh.2024.1428396.
45. Cestonaro C, Delicati A, Marcante B, Caenazzo L, Tozzo P. Defining medical liability when artificial intelligence is applied on diagnostic algorithms: a systematic review. Front Med (Lausanne). 2023 Nov 27;10:1305756. doi: 10.3389/fmed.2023.1305756.
46. Mennella C, Maniscalco U, Pietro GD, Esposito M. Ethical and regulatory challenges of AI technologies in healthcare: A narrative review. Heliyon. 2024 Feb 15;10(4):e26297. doi: 10.1016/j.heliyon.2024.e26297.
47. Wong LPW. Artificial Intelligence and Job Automation: Challenges for Secondary Students' Career Development and Life Planning. Merits. 2024 Dec;4(4):370–99. doi: 10.3390/merits4040025.
48. Khakpaki A. Advancements in artificial intelligence transforming medical education: a comprehensive overview. Med Educ Online.

0(1):2542807.
doi: 10.1080/10872981.2024.2542807.

49. Lawal O, Elechi K, Adekunle F, Farinde O, Kolapo T, Igbokwe C, et al. A Review on Artificial Intelligence and Point-of-Care Diagnostics to Combat Antimicrobial Resistance in Resource-Limited Healthcare Settings like Nigeria: Review Article. Journal of Pharma Insights and Research. 2025 Apr 5;3(2):166–75. doi: 10.69626/jpir.2025.03.019.
50. Ni Y, Jia F. A Scoping Review of AI-Driven Digital Interventions in Mental Health Care: Mapping Applications Across Screening, Support, Monitoring, Prevention, and Clinical Education. Healthcare. 2025 Jan;13(10):1205. doi: 10.3390/healthcare13101205.
51. Faiyazuddin Md, Rahman SJQ, Anand G, Siddiqui RK, Mehta R, Khatib MN, et al. The Impact of Artificial Intelligence on Healthcare: A Comprehensive Review of Advancements in Diagnostics, Treatment, and Operational Efficiency. Health Sci Rep. 2025 Jan 5;8(1):e70312. doi: 10.1002/hsr2.70312